SYMPOSIUM FF

GaN, AlN, InN, and Related Materials

November 28 - December 2, 2005

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* Invited paper

SESSION FF1: UV and White Light LEDs
Chair: Russ Dupuis
Monday Morning, November 28, 2005
Grand Ballroom (Sheraton)

8:00 AM *FF1.1
Deep Ultraviolet Light Emitting Diodes with Emission below 300 nm. M. Asif Khan, Department of Electrical Engineering, University of South Carolina, Columbia, South Carolina.

Recently several groups including ours have reported on III-Nitride deep ultraviolet (UV) ($\lambda <$ 300 nm) light-emitters. The interest in these devices stems from their potential applications in bio-chemical detection, air/water purification and bio-medical instrumentation. The focus of the current research is towards increasing the powers, efficiency and operation life-times. In addition we are also aiming to push the emission wavelengths well below 260 nm and fabricate devices with micro-pixel geometries. This should enable integration with conventional phosphors to produce RGB light sources with independent pixel control. In this paper we will report the results from our current research which has yielded 280 nm emission (100 μm x 100 μm) square geometry devices with powers above 2 mW at pump currents of only 20 mA. We have also succeeded in fabricating 280 nm interconnected micro-pixel LEDs with milliwatt powers and operation lifetimes well over 1000 hours. Some preliminary results of devices with independent micro pixel control for potential RGB displays and DNA micro-array testing will also be presented. These devices were integrated with micro-optical elements to improve the collimation and coupling of the emitted deep-UV light. Our presentation will discuss the details of the materials growth, device fabrication and testing. In addition we will review the results from our work and the other research groups to provide a snapshot of the state-of-the art.

8:30 AM FF1.2
AlGaN Deep Ultraviolet Light-Emitting Diodes with Vertical Structure. Koji Kawasaki[1], Choshiro Koike[1], Misaichi Takeuchi[2,1] and Yoshinobu Aoyagi[1,2]; [1]Tokyo Institute of Technology, Yokohama, Japan; [2]RIKEN, Wako, Japan.

High-power deep-UV light-emitting diodes (LEDs) and laser diodes based on AlGaN materials are required for environmental and medical use such as water purification, dioxin decomposition and sterilization. In general, AlGaN materials are grown on insulating sapphire substrates by MOCVD; however, AlGaN devices on sapphire substrate have several problems such as current crowding and self-heating due to high resistivity of thin n-type AlGaN layers. In this work, a new type of AlGaN LEDs, in which the sapphire substrate was removed by laser-assisted lift-off process and the transparent electrode was deposited on n-type AlGaN surface in order to flow the current from the anode to the cathode vertically, was fabricated for realization of future high-power deep-UV LEDs. Especially, our target wavelengths are 325 nm (He-Cd laser) and 245 nm (Hg lamp). This is the first report of AlGaN LEDs fabrication using laser-assisted lift-off tequnique. For the growth of deep-UV LEDs, 2.4um n-type AlGaN buffer layer was deposited after thin GaN buffer layer growth on the double-side polished (0001) sapphire substrate. Then an n-type Al0.3Ga0.7N layer was deposited and multiple-quantum wells consisting of 3 nm Al0.15Ga0.85N layers were deposited. Then, it was followed by a p-type Al0.3Ga0.7N layer, and capped by a thin p -GaN contact layer. After Ni/Au p-type electrode was deposited on the p -GaN surface, it was annealed at 450oC for 10min. Then the electrode surface and GaAs substrate was bonded each other by the AuGe solder. The laser-assisted lift-off process was carried out using a Q-switched Nd:YVO laser (266nm) defocused at the AlGaN active layer. Then the n-type surface was etched by RIE and finally the LED was fabricated by the n-type transparent metallic electrode-deposition on the n-AlGaN surface. In these devices, light emission by current injection was uniformly observed at only n-type transparent electrode region. This is evidence that the electrons were vertically injected to the p-type electrode. Main emission peak wavelength was 322 nm as initial design. Emission intensity was almost the same as that of the conventional flip-tip type LED. The detail in these devices will be presented at the conference.

8:45 AM FF1.3
AlGaN Based Sub-250 nm Light-Emitting Diodes. Jianping Zhang[1], Xuhong Hu[1], Jianyu Deng[1], Y. Belinko[1], A. Lunev[1], T M Katona[1], Remis Gaska[1] and Asif M Khan[2]; [1]Sensor Electronic Technology, Columbia, South Carolina; [2]University of South Carolina, Columbia, South Carolina.

We have recently demonstrated AlGaN based 280 nm light emitting diodes (LEDs) with output power exceeding 2.5 mW at 20 mA dc. This represents a 2x improvement in wall-plug efficiency over previously reported diodes emitting at this wavelength. We have also demonstrated UV LEDs with emission ranging from 254 - 300 nm with milliwatt-level output power. LEDs emitting at even shorter wavelengths, however, would add additional discrimination and sensitivity for many biotech, biomedical, and fluorescence based detection systems that is not achievable with longer wavelengths. Despite the necessity for very short wavelength UV LEDs, fundamental material challenges must be overcome to demonstrate these devices. Sub-250 nm LEDs require AlxGa1-xN with aluminum content ranging from 60-80%. This limits the AlGaN growth rate as well as the material quality, since Al-adatoms are less mobile and have stronger affinity to impurities. Secondly, high Al-content AlGaN alloys have larger dopant ionization energies for both n-type (Si), and p-type (Mg) dopants. This results in all electrically active areas of the device structure having lower conductivity which affects ohmic contact fabrication and increases device self-heating. Thirdly, the fundamental radiative recombination rate also decreases as the Al-content increases, resulting in lower quantum efficiency for these devices. In this talk, we will present our results on sub-250 nm LEDs and discuss the challenges that need to be overcome to demonstrate high power UV LEDs emitting in this wavelength regime. We grew 246 nm UV LEDs by Migration-Enhanced Metalorganic Chemical Vapor Deposition (MEMOCVD). MEMOCVD is designed to maximize the migration of low surface mobility adatoms like Al by utilizing different source pulses to grow material. It is ideally suited for high-Al-content AlGaN growth. Our preliminary results demonstrate the feasibility of sub-250 nm LEDs. Initial on-wafer power measurements showed a dc power of 5-10 uW at 20 mA with an emission wavelength as short as 246 nm. Fig. 1 shows the clean spectral quality for electroluminescence spectra of a 246 nm LED wafer at different driving currents. We will present fully packaged very deep UV LED data and discuss the role of aluminum incorporation into the AlGaN active region on LED performance.

9:00 AM FF1.4
270 nm Deep UV LEDs with a Micro-Pixel Design. Shuai Wu, Ajay Sattu, Li Yan, Yadav Praveen, Hasan Faruq, Wenhong Sun, Maxim Shatlov, Vinod Adivarahan and Asif Khan; Electrical Engineering, University of South Carolina, Columbia, South Carolina.

III-Nitride deep ultraviolet (UV) emitters ($\lambda <$ 280 nm) are potentially viable sources for bio-chemical detection, air/water purification and bio-medical instrumentation. For these applications, high power, high efficiency and operation life-time over 10000 hrs are highly desirable. In past we have reported milliwatt power (at 20 mA) 280 nm deep UV LEDs on sapphire substrates. These square geometry devices had pixel sizes of 100um x 100um. This small pixel size was required to avoid current crowding which becomes a key issue due to the thin high Al-content (x>0.55) AlxGa1-xN buffer layers. Thus device currents even as low as 20 mA result in pump densities as high as 200 A/cm2. This leads to excessive device heating and premature saturation of the output power in DC pumping. In addition the device lifetime is also reduced because of the heating from the high pump current densities. We now report using a new interconnected micro-pixel array design for deep UV LEDs with peak emission at 270 nm. This design provides a uniform current spreading in each micro-LED and hence the current crowding is completely avoided. As a result the effective p-contact area is increased substantially. This, in turn, leads to significantly lower differential resistance and turn-on voltage. The reduction of device self-heating also increases the life-time of the micro-pixel LEDs. Deep UV LEDs having a 10x10 interconnected micro-pixel array geometry with the pixel diameter of 22um were then fabricated. At the same time, square geometry LED devices with pixel sizes of 200um were also fabricated from the same wafer. Note the two device type have nearly identical emission areas. . Both devices were then flip-chip mounted onto TO-66 headers for thermal management. At 20 mA dc pump current the 10x10 micro-pixel design LED showed the operating voltage to be 0.7V lower than that for the square device. This we believe is due to the reduction in the series resistance and the turn-on voltage. As a result, the life-time (the time for the power to go down from 100% to 70%) was 120 hrs for the conventional 200μm x 200μm square, whereas for the micro LED it was about 800 hrs. To have an in depth understanding of LED thermal characteristics, computational analysis of temperature distribution throughout LED package has been performed using ANSYS FEA software. LED package with square geometry or micro-pixel LED were simulated with the appropriate boundary conditions. From the numerical results it was found that under dc bias of 20mA the junction temperature increases by 18° above ambient for the square geometry LEDs, whereas for the micro-pixel array design the temperature increase was only 8°. This shows a 55% improvement in device thermal impedance from the package. In this paper preiliminary results of independent addressing of the micro-pixels for potential RGB displays and DNA micro-array testing will also be presented.

9:15 AM FF1.5
Low frequency noise of GaN−based UV LEDs. Shayla Sawyer[1], S. L. Rumyantsev[1,3], N. Pala[1,2], M. S. Shur[1], Y. U. Bilenko[2], J. P. Zhang[2], X. Hu[2], A. Lunev[2], J. Deng[2] and R. Gaska[2]; [1]Electrical Computer and Systems Engineering, Rensselaer Polytechnic Institute

Center for Broadband Data Transport Science and Technology, Troy, New York; [2]Sensor Electronic Technology, Inc., Columbia, South Carolina; [3]On leave from the Ioffe Institute of Russian Academy of Sciences, St-Petersburg, Russia, Russian Federation.

UV LEDs are finding numerous applications in detection of hazardous biological agents and in fluorescence experiments, where signal-to-noise ratio is crucial for the overall system performance. In this paper, we characterize and interpret the low frequency noise properties of deep UV GaN-based LEDs with improved characteristics. These LEDs have a considerably smaller noise compared to all other UV sources, including the first generation of UV LEDs. We ascribe this improvement to a better design and to the MEMOCVD℠ growth technology that improved the overall material quality and resulted in much better LED performance. Low frequency fluctuations of current and light intensity were measured for different types of LEDs with wavelength from 265 to 375nm. The comparison of the noise characteristics for different LEDs was made using our new figure of merit for optical noise. The LED light intensity fluctuations were reduced more than one order of magnitude compared with the first generation LEDs. We also discuss the optimum biasing conditions for minimizing the LED noise. The current noise spectra reveal the contribution of the generation recombination noise at low currents. These results allowed us to analyze deep levels, which contribute to noise and affect the light generation process. We also present the signal-to-noise analysis for the entire LED −photodetector system that demonstrates how one can optimize the overall signal-to-noise characteristics. The later analysis is especially important for biological hazardous detection systems in order to minimize the number of false positives and false negatives.

9:45 AM FF1.6
Deep UV AlGaN based light emitting diodes grown by gas source molecular beam epitaxy. Sergey Nikishin, Boris Borisov, Vladimir Kuryatkov, Mark Holtz and Henryk Temkin; Texas Tech University, Lubbock, Texas.

We report the optical and electrical properties of deep ultraviolet light emitting diodes (LEDs) based on digital alloy structures (DAS) of AlN/Al0.08Ga0.92N grown by gas source molecular beam epitaxy with ammonia. DASs consisting of Al0.08Ga0.92N wells, 0.50 nm or 0.75 nm thick, and AlN barriers, 0.75 nm to 1.5 nm thick, were grown on sapphire substrates. For DASs with effective bandgap of 5.1 eV we obtain room temperature electron concentrations up to 1x1019 cm-3 and hole concentrations of 1x1018 cm-3. Based on these results we prepared double heterostructure (DH) LEDs operating in the range of 250 to 290 nm. In all LEDs, the p- and n-type cladding layers were grown with the same effective bandgap corresponding to xAlN $\sim$ 0.72. The emission wavelengths were controlled through the effective bandgap of the active region. We will discuss the possible ways for increase of LED efficiency. We will show that the addition of undoped, 10 nm thick, AlN barriers on each side of the active layer, results in significant improvement (by at least a factor of 2.5) in the emission efficiency without any change in the electrical characteristics. The introduction of AlN barriers also results in the elimination of the parasitic emission at 320 nm, even under very low excitation current density of 40 A/cm2. Preliminary experiments show that DASs grown on bulk AlN substrates have 3-4 times higher luminescence efficiency than DASs grown on sapphire. We will discuss a significant improvement in the room temperature cathodoluminescence efficiency (by factor of 100) of AlGaN quantum wells when the 3D growth mode is induced by reduced flux of ammonia. This work is supported by DARPA (under a contract monitored by Dr. J. Carrano), NSF (ECS0323640 and ECS0304224), NATO Science for Peace (974505), and the J. F Maddox Foundation.

10:00 AM FF1.7
A Growth Method to Reduce Dislocation Density and Control Stress in AlN Films Grown on Sapphire.
Andrew A. Allerman, Mary H. Crawford, Stephen R. Lee, David M. Follstaedt, Paula P. Provencio and Arthur J. Fischer; Sandia National Laboratories, Albuquerque, New Mexico.

AlN films grown on sapphire substrates enable the fabrication of bottom-emitting LEDs with deep ultra-violet emission (λ<300nm). However, these films typically exhibit both threading-dislocation densities exceeding 1e10cm-2 and stress-induced cracking in layers exceeding approximately 1μm in thickness. We present a method for AlN film growth that produces threading-dislocation densities less than 5e9cm-2. This method involves manipulation of growth conditions following initial film nucleation and has been used to grow crack-free AlN films exceeding 3μm in thickness. Using these AlN films as template layers, we produced Si-doped AlGaN films (with $\sim$50-70% AlN mole fractions) that have improved electron mobilities and higher doping efficiencies. These improvements suggest a reduced level of compensation in the AlGaN due to reductions in dislocation density. The presentation will also include the performance of LEDs emitting in the deep UV (<300nm) that have been fabricated with lower dislocation density AlN-AlGaN films. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94-AL-85000. This work is also supported by DARPA under the SUVOS program managed by LTC J. Carrano.

10:15 AM FF1.8
A Novel Solid State General Illumination Source. David Nicol[1], Ian Ferguson[1,2] and Ali Asghar[1]; [1]Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, Georgia; [2]Materials Science Engineering, Georgia Institute of Technology, Atlanta, Georgia.

The lighting industry is on the cusp of a major revolution with the development of new illumination sources based on light emitting diodes (LEDs) called Solid State Lighting (SSL). SSL is currently widespread in niche applications such as signage, backlighting, mobile devices, traffic signals, and large area displays, but no significant penetration has been achieved in the general illumination market. In niche markets one or more of the following key attributes make solid state sources attractive alternatives to conventional illumination technologies: saturated color, small size, energy efficiency, robustness, and controllability. However, in general illumination different criteria such as broadband, high color rendering capability, and appropriate correlated color temperature make a SSL solution more difficult to construct. In fact, in many cases designers and architects are seeking added functionality such as dynamic spectral control. Currently, no available SSL technologies incorporate all the necessary attributes for general illumination. Thus there is a need to design novel devices that lend themselves to a SSL general illumination solution. A broadband spectrally dynamic solid state illumination source has been developed. This new device is comprised of a three terminal dual LED structure. Separate control of two MQW regions can be achieved in this arrangement with a tunnel junction acting as a buried current spreading layer. A combination of multiple phosphors are then pumped by either or both of the wavelengths emitted from the dual LED to produce white light of a variable power spectrum. Preliminary phosphor analysis shows such a scheme to be viable for use in a spectrally dynamic broadband general illumination source. The correlated color temperature of the emitted white light can be controlled by adjusting the relative intensities of the two pump wavelengths. This functionality differs from other phosphor converted LEDs that are inherently spectrally static. It also improves upon the illumination properties of RGB dynamic solid state sources with peaked spectra, by employing broadband phosphor. A dynamic, controllable, phosphor converted solid state light source has not been developed previous to this work.

10:30 AM FF1.9
Improved Efficiency of Polychromatic Generation with CdSe Nano-Crystals Coated on an InGaN/GaN Quantum-Well Light-Emitting Diode. Dong-Ming Yeh[1], Chih-Feng Lu[1], Chi-Feng Huang[1], Tsung-Yi Tang[1], Horng-Shyang Chen[1], Jian-Jang Huang[1], Chih-Chung Yang[1], Chih-Min Chuang[2] and Wei-Fang Su[2]; [1]Institute of Electro-Optical Eng., National Taiwan University, Taipei, Taiwan; [2]Dept. Material Science and Eng., National Taiwan University, Taipei, Taiwan.

The techniques of color mixing for polychromatic display and white-light generation are important for the developments of micro-display and solid-state lighting. For polychromatic display, multi-element light-emitting diode (LED) arrays of different colors are widely used. To implement white-light generation, polymer phosphors are usually placed on either blue or UV LEDs for generating complementary colors. However, the use of phosphors normally results in poor efficiency and difficulty in packaging. In this research, we adopt an all-semiconductor approach for implementing polychromatic generation. We coat CdSe nano-crystals on an InGaN/GaN multiple quantum-well (QW) structure. The QW structure emits blue light or blue/green light. The CdSe nano-crystals absorb the blue/green light from the QW structure and emits red light. The absorption and emission wavelengths of the CdSe nano-crystals depend on the size of CdSe nano-crystal and its coating of ZnS. To enhance the energy transfer efficiency, the photon emission wavelength of the InGaN/GaN QW structure and the major absorption spectral range of the CdSe nano-crystals must be matched. Also, to implement the required color mixture, the emission wavelengths and intensities from the QWs and nano-crystals must be well adjusted. For these purposes, the QW composition and well width and the size of CdSe nano-crystal need to be carefully designed. In our current implementation, the CdSe nano-crystals (4.5 nm in size with a ZnS coating of 0.2 nm in thickness) have a reasonably strong absorption coefficient around 450 nm and emit light at 599 nm. Therefore, we can mix the blue and red colors. To enhance the energy transfer efficiency from blue to red, we fabricate holes with the diameters ranging from 50 to 300 microns on

the top of the LED for filling up with the CdSe nano-crystal solution. The nano-crystals in the holes can absorb the emitted blue photons from the QW structure more easily, leading to stronger red emission. Besides the mixing of blue and red colors, the green color can be added by using an epitaxial sample of two diodes, which is grown with two sets of QW for blue and green emissions.

SESSION FF2: VPE:GaN
Chair: Jung Han
Monday Morning, November 28, 2005
Grand Ballroom (Sheraton)

10:45 AM FF2.1
Compressive Strain Relaxation in AlGaN on AlN by Inclined Threading Dislocations. David M. Follstaedt, Stephen R. Lee, Jerrold A. Floro, Paula P. Provencio, Andrew A. Allerman and Mary H. Crawford; Physical, Chemical and Nano Sciences Center, Sandia National Laboratories, Albuquerque, New Mexico.

Hexagonal GaN is being alloyed with AlN and InN to tailor the bandgap for optical emission ranging from the visible to the ultraviolet. To develop light-emitting devices with optimum output in the deep UV, we have been growing Al0.61Ga0.39N by MOCVD on AlN buffer layers that were grown on sapphire. Our growths showed a different microstructure when examined with cross-section TEM: the vertical threading dislocations emerging from the AlN bent by about 19 degrees upon entering the compressively strained AlGaN. Such inclined dislocations have been seen before in Si-doped, compressively strained AlGaN (Cantu et al., Appl. Phys. Lett. 83, 674 (2003)). In our structure, however, the dislocations bend within ∼15nm of the interface even though Si was not introduced until 120 nm above the interface, demonstrating that Si is not required to produce inclined dislocations. The inclined dislocations have been shown to relax the strain according to a model by Romanov and Speck (Appl. Phys. Lett. 83, 2569 (2003)), if they have an edge component to their Burgers vector (b = a). Using this model with our dislocation density and tilt angle, we account for 75% of the relaxation in the AlGaN as determined by x-ray diffraction; the remainder is due to some misfit dislocations found at the interface. In addition, we have verified the linear dependence of this relaxation on thickness of the strained layer that is predicted by the model. It is important to understand this relaxation mechanism since excessive strain of the material can induce cracking and also influence the emission wavelength and intensity of LEDs. While the effects of inclined dislocations on relaxation appear quantitatively well understood, comparisons with relaxation in other strained GaN-based alloys lead to important questions about when this mechanism operates. First, inclined dislocations were not reported for relaxation of compressively strained InGaN on GaN (Srinivasan et al., Appl. Phys. Lett. 83, 5187 (2003)). Secondly, inclined dislocations appear equally capable of relaxing tensile-strained layers; however, AlGaN grown on GaN was found to relax by a combination of cracking plus misfit dislocations, while threading dislocations remained vertical (Floro et al., J. Appl. Phys. 96, 7087 (2004)). It is likely that details of the growth process (temperature, growth rate, gasses used, V/III ratio, etc.) and the growth mode established to produce the structure (islands or planar; degree of surface roughness) play a role in controlling this mechanism. Nonetheless, the differences between these systems appear striking. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energys National Nuclear Security Administration under contract DE-AC04-94-AL-85000.

11:00 AM FF2.2
Correlation Between Stress Evolution and Threading Dislocation Density Evolution during MOCVD Growth of GaN on (111) Si. Srinivasan Raghavan[1], Xiaojun Weng[1,2], Elizabeth Dickey[1] and Joan M. Redwing[1]; [1]Department of Materials Science and Engineering, The Pennsylvania State University, University Park, Pennsylvania; [2]The Electro-optics Centre, The Pennsylvania State University, University Park, Pennsylvania.

In the absence of homoepitaxial substrates, thin films of the group III-A(Ga, Al and In) nitrides are deposited heteroepitaxially on sapphire, SiC and Si. One consequence of the heteroepitaxy is that growth occurs in either the 3-D (Volmer Weber) or 2-D + 3-D (Stranski-Krastanov) mode. Hence, film growth invariably involves the coalescence of discrete islands with the concomitant formation of threading dislocations that accommodate tilt and twist between neighboring islands. The threading dislocation density is highest at the beginning of growth and decreases in density to about 108-1010 /cm2 in films > 1 ?m in thickness. Using a combination of in-situ measurements of growth stress and cross sectional TEM measurements, it is observed that the reduction in threading dislocation density in AlGaN films deposited on Si occurs mainly when the film in growing under a compressive stress. The reduction in threading dislocation density in turn contributes to a relaxation of the compressive stress in the film at the growth surface and its eventual transition to a tensile stress in the absence of other compressive sources of stress. It is shown that this relation between threading dislocation density reduction and stress evolution can be exploited to grow crack free GaN layers >1 ?m thick on (111)Si using graded AlGaN buffer layers. The change in lattice parameter on grading from AlN to GaN is the source of compressive stress in this case. Thus, even though the film starts growing under tension it eventually transitions into an incremental compressive stress. It is seen that increasing the thickness of the graded layer increases the thickness of the segment that grows under compression as well. Hence, if the layer is thick enough, ∼1 ?m, all threading dislocation density reduction occurs in the AlGaN layer itself during the compressive portion. Thus, the subsequent GaN layer not only has lower defect density but also continues to grow under a compressive stress. This compressive stress helps offset the tensile thermal expansion mismatch stress on cooling and enables an increase in the critical thickness for cracking. In contrast, when a GaN layer is deposited directly on the commonly used 100 nm thick AlN buffer layer, all dislocation density reduction occurs in the GaN layer itself. Thus, the compressive stress arising out of the lattice mismatch between GaN and AlN is quickly neutralized within 100 nm of the buffer layer interface and the film transitions into a tensile stress. In addition, once this happens, dislocation density reduction ceases and the film ends up with a relatively higher defect density. The critical thickness for cracking was increased by a factor of 4 -10 and the integral breadths of (0002) and (10-12) peaks were decreased by a factor of 2 and 4 respectively, for GaN grown on a 2 ?m thick linearly graded AlGaN buffer layer in comparison to that grown on a 100 nm thick AlN layer.

11:15 AM FF2.3
Strain Relaxation Mechanisms in thin AlN Heterostructures on GaN. S. R. Lee, D. D. Koleske, J. A. Floro and K. C. Cross; Sandia National Laboratories, Albuquerque, New Mexico.

Strain-relaxation mechanisms remain poorly understood for the thin AlN layers used for both mobility enhancement in HEMTs and crack-suppression in LEDs and DBRs. Here, we study these mechanisms using a combination of atomic-force microscopy, transmission electron microscopy, x-ray diffraction reciprocal-space mapping, and in-situ wafer-curvature measurements. We examine single AlN heterolayers grown to thicknesses between 0.5 and 60 nm; the layers are grown on GaN pseudo-substrates by MOCVD under ammonia-rich conditions. AFM images show a striking evolution of the AlN surface morphology with layer thickness. At a thickness of 0.5 to 1 nm, surface roughening occurs producing 20-nm-diameter islands that densely cover the entire surface. As thickness rises from 2 to 4 nm, quasi-linear channels emerge along <11-20> directions in competition with the initial roughening. Since the critical thickness for surface fracture of AlN on GaN is ∼3.4 nm, we hypothesize that these channels result from nanometer-scale fracture. Intersecting channels yield an array of faceted flat-topped domains ∼70 nm in width. As thickness exceeds 7.5 nm, channel formation stops, and these domains begin to lose their faceted shape as they laterally coarsen in size. In-situ wafer-curvature measurements of stress suggest that misfit dislocations begin to enter the AlN layer concomitant with channel formation. To verify this inference, we are currently performing TEM studies of 3.0 and 7.5 nm thick AlN layers. Further XRD studies of 15-60 nm thick AlN reveal that the layers are 80% strain relaxed at a thickness of 15 nm. By comparing XRD measurements of strain before and after capping the AlN layers with thick GaN, we find that half of this relaxation is due to the channeled surface morphology, while the other half is due to misfit dislocations. Finally, as thickness grows beyond 15 nm and the surface becomes smoother, elastic relaxation due to surface morphology decreases while plastic relaxation due to misfit dislocations increases. These last effects offset one another such that total relaxation remains constant at ∼80-85% as the thickness reaches 60 nm. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

11:30 AM FF2.4
Reduction of Dislocation Density in GaN Layers Grown By Multi Step Technique. Maxim Odnoblyudov[1], Teemu Lang[2] and Vladislav Bougrov[1]; [1]A.F.Ioffe Physico-Technical Institute, St.Petersburg, Russian Federation; [2]Optoelectronics Laboratory, Helsinki University of Technology, Espoo, Finland.

One of the main difficulties in the crystal growth of high-quality gallium nitride (GaN)-based devices is the lack of lattice-matched substrates. Lattice mismatch results in a high density of threading dislocations (TD) in nitride films. The two step method, which involves deposition of a thin GaN layer (nucleation layer) at a low temperature with subsequent high temperature annealing followed by high temperature growth, has been successfully applied to increase

the quality of GaN epilayers on sapphire. The method can be used to reduce the threading dislocation density to 5-7x 10^8 cm^{-2}. It provides a large density of high crystalline quality GaN islands on the sapphire surface. These islands act as nucleation centers for further high temperature growth. It is believed that threading dislocations in this case are generated at the coalescence boundaries between the islands in result of twist misorientation between the islands. Thus, reduction of island density and suppression of dislocation generation at the coalescence boundaries seem to be a promising direction for research targeting to the reduction of threading dislocation density in GaN epilayers on sapphire. One of the most efficient modern techniques for the reduction of island density is pre-growth treatment of a sapphire substrate with silane. This allows to reduce the density of nucleation sites down to 1x10^8 cm^{-2} compared to that of more than 10^9 cm^{-2} for the standard two step method. In this work we report on the multi-step technique, which does not require silane treatment and enables the growth of high crystalline quality GaN epilayers on sapphire with a threading dislocation density of 7-8x$10^7$$cm^{-2}$. The process consists of the growth of GaN islands by consecutive low temperature-GaN deposition and annealing steps and provides independent control of the size and density of the islands. By varying the number of steps, the amount of low temperature material deposited in each step and the annealing temperature and time, an island density of as low as 10^7cm $^{-2}$ can be achieved. The island size can also be controlled within a range of 50 to 1000 nm range. Further high temperature overgrowth parameters are chosen to stimulate growth of high index facets of the islands. This provides favorable conditions for coalescence of the islands and allows reducing the amount of dislocations generated at coalescence boundaries. This growth mode also stimulates inclination of the threading dislocations towards the high index crystalline facets, which minimizes the dislocation energy. The inclination facilitates reactions between the threading dislocations and acts as an additional factor, which efficiently reduces the dislocation density with increasing epilayer thickness. The theoretical model describing threading dislocation inclination and reduction of the dislocation density due to reactions between the dislocations is also presented.

SESSION FF3: Dopants and Defects
Chair: Takao Miyajima
Monday Afternoon, November 28, 2005
Grand Ballroom (Sheraton)

1:30 PM FF3.1
H Enhancement of N Vacancy Migration in GaN.
Ryan R. Wixom and Alan F. Wright; Sandia National Laboratories, Albuquerque, New Mexico.

Hydrogen is widely understood to compensate Mg in GaN grown via organometallic vapor phase epitaxy (OMVPE). However, there is increasing evidence of a secondary compensating species, which has been speculated to be the N vacancy. While the experimental evidence is largely indirect, theory clearly predicts the N vacancy to be the most stable native defect. These two compensators should simultaneously exist in OMVPE grown material and their mobility is technologically important. Migration of the isolated species has been previously reported, but there is no a priori indication of how H will effect the mobility of the N vacancy. Using density functional theory, we have investigated the migration of the N vacancy in the presence of H, and found that the interplay of the two species results in a 0.58 eV reduction of the vacancy migration barrier. At nitride OMVPE temperatures, this will increase the predicted diffusion length by more than an order of magnitude.

1:45 PM FF3.2
Remarkable Increase of Deep UV Emission from Quaternary InAlGaN by Reducing Oxygen and Carbon Impurities.
Tomoaki Ohashi[1,2], Hideki Hirayama[1], Koji Ishibashi[1] and Norihiko Kamata[2]; [1]Advanced Devices Laboratory, RIKEN, Saitama, Japan; [2]Saitama Univ., Saitama, Shimo-Okubo, Sakura-ku, Japan.

For the realization of commercially available deep-ultraviolet (UV) light sources, quaternary InAlGaN-based UV emitter is considered to be quite useful, because it emits efficiently at wavelength between 280-380 nm UV-band at room temperature (RT) due to In-incorporation effects even on high-density threading dislocation (TD) buffers or substrates. In this work, we demonstrate significant increase of 295-330-nm-band deep-UV emission from quaternary InAlGaN by reducing oxygen and carbon impurities grown by metalorganic vapor phase epitaxy (MOVPE). We also demonstrate pulsed and CW operation of bright UV light-emitting diodes (LEDs) with quaternary InAlGaN quantum well (QW) emitting layers. The samples were grown on sapphire substrates by low pressure MOVPE. We obtained 295-350 nm single-peaked intense emission at RT from quaternary InxAlyGa1-x-yN by changing In and Al incorporation (In:1-5%, Al:15-60%). In order to reduce the concentration of impurities, we controlled the growth pressure of InAlGaN. We observed a significant reduction of oxygen and carbon impurities in InAlGaN layers measuring by secondary ion mass spectroscopy (SIMS). Both oxygen and carbon impurity concentrations were reduced by 3-5 times by incresing the growth pressure from 38 to 200 Torr. The peak intensities of 295-330 nm UV photoluminescence (PL) from InAlGaN were increased by approximately 5 times by incresing the growth pressure. We also observed remarkable reduction of the yellow-band emissions and the decrease of the full width at half maximum (FWHM) of UV PL from InAlGaN due to the effects of reducing impurity concentrations. We then fabricated UV-LEDs with Inx1Aly1Ga1-x1-y1N/Inx2Aly2Ga1-x2-y2N multi(M) QW emitting region on high-quality AlN buffer layer directly grown on sapphire substrate with high growth temperature (HT). Single-peaked intense electroluminescence (EL) was obtained with wavelengths between 308-350 nm. In the presentation, the enhancement of UV output power by controlling growth pressure of InAlGaN QW layers will be discussed.

2:00 PM FF3.3
Spatially Resolved Synchrotron Radiation Investigations of Dopants in GaN.
Michael Siebert[1], Thomas Schmidt[1], Jan-Ingo Flege[1], Stefan Figge[1], Sven Einfeldt[1], Angelika Pretorius[1], Subhashis Gangopadhyay[1], Joerg Zegenhagen[2], Tien-Lin Lee[2], Lucca Gregoratti[3], Alexei Barinov[3], Detlev Hommel[1] and Jens Falta[1]; [1]Institute of Solid State Physics, University of Bremen, Bremen, Germany; [2]European Synchrotron Radiation Facility, Grenoble, France; [3]ELETTRA Synchrotron Light Source, Basovizza, Italy.

Depending on the Mg and Si dopant concentration, a variety of defects such as inversion domains or V-shaped defects has been reported to occur in GaN films [1, 2]. Hence, detailed knowledge about the interplay between dopant concentration and defect formation may allow to optimize the dopant concentration with respect to the growth of films with high crystal quality and sufficiently high dopant homogeneity. In order to obtain structural information on doped GaN systems on both the micro- and the mesoscopic scale, we performed synchrotron radiation measurements applying x-ray standing waves (XSW), x-ray photoelectron spectroscopy (XPS) and spatially resolved XPS (ESCA-microscopy) for different dopant concentrations. All samples were grown by metal-organic vapor phase epitaxy on sapphire (0001) substrates. The measurements were performed ex-situ at the European Synchrotron Radiation Facility (ESRF, France), the Hamburg Synchrotron Radiation Laboratory (HASYLAB, Germany) and the ELETTRA Synchrotron Light Source (Italy). For the first time, XSW measurements, which allow to directly determine the atomic incorporation sites, were successfully performed on light trace elements in GaN. In order to minimize influences of lacking crystal quality on the XSW signal, the measurements were performed in backscattering geometry using (002) and (004) Bragg reflections on samples with a 3 micron thick undoped GaN film to establish a standing wave field in a 350 nm thick doped film on top. Our results demonstrate a prevalent incorporation on substitutional sites for either species and a systematic variation of incorporation on additional sites as depending on the dopant concentration. XPS measurements on Mg doped samples before and after sputtering or annealing revealed a strong segregation tendency also at very low Mg concentrations (4x10$\hat{1}$9/cm$\hat{3}$). Additionally, segregation was also observed for Si doped samples. The characteristics of Si surface segregation were investigated in detail with ESCA-microscopy which allows to quantify the chemical surface composition with spatial resolution. These measurements yielded preferential Si agglomeration at faceted steep surface cracks, which were oriented along high symmetry crystal directions. [1] Z. Liliental-Weber, M. Benamara, W. Swider, J. Washburn, I. Grzegory, S. Porowski, R. D. Dupuis, C. J. Eiting, Physica B, 273-274 (1999) 124 [2] T. Nakamura, S. Mochizuki, S. Terao, T. Sanoa, M. Iwaya, S. Kamiyama, H. Amano, I. Akasaki, J. Cryst. Growth, 237-239 (2002) 1129

2:15 PM FF3.4
Growth and p-type Doping in Al-rich AlGaN Alloys.
Mim Lal Nakarmi, Neeraj Nepal, Cristofer Ugolini, Jingyu Lin and Hongxing Jiang; Kansas State University, Manhattan, Kansas.

Al-rich AlGaN alloys are ideal materials for the development of chip-scale optoelectronic devices such as deep ultraviolet (UV) emitters and detectors operating at wavelengths down to 200 nm. Highly conductive n- and p-type Al-rich $Al_xGa_{1-x}N$ alloys are required to achieve practical deep UV emitters ($\lambda < 300$ nm). We report on the growth and Mg-doping in Al-rich $Al_xGa_{1-x}N$ alloys by metalorganic chemical vapor deposition (MOCVD) on sapphire (0001) substrate. Optical properties were probed by deep ultraviolet (UV) time-resolved photoluminescence (PL) spectroscopy and variable temperature Hall-effect measurement has been employed to study the electrical properties of Mg-doped AlGaN alloys. In Mg-doped AlGaN, nitrogen vacancies (V_N) have low formation energy and act as compensating centers for Mg acceptors and can be identified as a

donor-acceptor pair recombination. By minimizing the PL emission intensity associated with nitrogen V_N related transitions by varying the growth parameters, we have achieved p-$Al_xGa_{1-x}N$ alloys with high x. Material with better optical and electrical quality show dominant acceptor-bound exciton and shallow donor to Mg acceptor level transitions at room temperature. We confirmed p-type conduction at elevated temperatures and the large binding energy of Mg acceptors in Al-rich $Al_xGa_{1-x}N$ (x > 0.7) alloys. Application of Mg-doped Al-rich AlGaN alloys to the UV optoelctronic devices are also discussed.

SESSION FF4: MBE:GaN

Chair: Steve Durbin
Monday Afternoon, November 28, 2005
Grand Ballroom (Sheraton)

3:30 PM FF4.1

The Use of Cathodoluminescence in Gallium Nitride During Growth to Determine Substrate Temperature. Kyoungnae Lee, Eric Schires and Thomas H. Myers; Physics, West Virginia University, Morgantown, West Virginia.

Accurate measurement of the substrate temperature during growth of gallium nitride by molecular beam epitaxy is crucial. Typically, thermocouples are usually used to measure the temperature of the back side of block which is holding the substrate. Alternatively, pyrometers are often used. However, there is a big range of an error. In-situ cathodoluminescence (CL) occurring during reflection high energy electron diffraction is a strong candidate to determine the growth temperature. The electron beam supplied by our RHEED gun has an energy of 13keV which was used for each measurement. CL was easily detected up to and beyond typical growth temperatures. The CL was directed into a monochromator using fiber optics. The final signal was detected with a photomultiplier tube. This technique appears quite useful to accurately and reproducably determine substrate temperature during growth. The CL could also be observed using a ccd camera. Thus, we investigated using the CL to image the sample during growth. This could be used to see temperature inhomogenaities, and potentially to map alloy composition fluctuations. We calibrated the wavelength vs. growth temperature by using narrow band-pass interference filters. Background subtraction with blanking the e-beam could be used to remove black body radiation and other undesired sources of light. For gallium nitride, the photon energy at the growth temperature of 750C is about 3.0eV. Using different filters, we can take a picture of e-beam on the surface of substrate for each filter and analyze the peak intensity using the line profile. We will present CL images of various samples at differing temperatures. This work was supported by the AFOSR MURI F49620-03-1-0330 monitored by Todd Steiner and Gerald Witt and by ONR Grants N00014-02-1-0974 and N00014-01-1-0571, both monitored by Colin E. C. Wood.

3:45 PM FF4.2

Reduction of Tilt and Twist in AlGaN Films Grown on (0001) Sapphire. Hock M. Ng and Theo Siegrist; Bell Labs, Lucent Technologies, Murray Hill, New Jersey.

$Al_xGa_{1-x}N$ epitaxial films are crucial for applications such as ultraviolet (UV) emitters and detectors. We report on the growth and x-ray characterization of $Al_xGa_{1-x}N$ films with a focus on the effects of initial growth conditions on the structural properties of the films. The $Al_xGa_{1-x}N$ films ($0 \leq x \leq 1$) were grown by plasma-assisted molecular beam epitaxy (MBE) on (0001) sapphire substrates. It was found that low temperature nitridation (~ 100 °C) and an AlN buffer layer grown by migration-enhanced epitaxy (MEE) played important roles in reducing the tilt and twist components of the $Al_xGa_{1-x}N$ films. The AlN buffer layer deposited on the nitridated surface was characterized by x-ray reflectivity. The interfacial roughness for a 25 nm AlN buffer layer was determined to be ~ 2 nm by fitting the measured curve with the calculated reflectivity. Without nitridation, no interference fringes were detected in the reflectivity measurement indicating a much rougher interface. This shows that low temperature nitridation is essential for maintaining a smooth growth front during the buffer layer growth. When MEE was employed for the AlN buffer growth, the reflection high energy electron diffraction (RHEED) pattern was more streaky compared to the case when the AlN buffer is grown with the conventional method of simultaneous Al and N fluxes. The full-width at half maximum (FWHM) of the rocking curves for symmetric on- and off-axis reflections were measured to determine the degree of tilt and twist, respectively. Off-axis scans were performed for (1 0 -1 1), (1 0 -1 2), and (1 0 -1 3) reflections and the twist component was extracted by extrapolating the angle of inclination to 90° following the analysis of Srikant *etal.* [1]. Detailed analysis of $Al_xGa_{1-x}N$ with x ~ 0.4 revealed that the sample grown without low temperature nitridation had a twist angle of 0.78° with an interdependence parameter of m = 0.55 while the sample with nitridation and an MEE AlN buffer showed a twist angle of 0.50° with a smaller interdependence parameter of m = 0.14. A more drastic improvement is seen in the FWHM of the (0002) reflection that relates to the tilt mosaic in the films. With nitridation and an MEE AlN buffer, the FWHM was reduced from 0.31° to 0.05°. [1] V. Srikant, J. S. Speck, and D. R. Clarke, J. Appl. Phys. 82, 4286 (1997).

4:00 PM FF4.3

Structural, Magnetic and STM Studies of CrGaN Grown by rf N-Plasma Molecular Beam Epitaxy. Muhammad B. Haider[1], Rong Yang[1], Hamad Al-Brithen[3], Costel Constantin[1], David C. Ingram[1], Arthur R. Smith[1], Gabriel Caruntu[2] and Charles J. O'Connor[2]; [1]Physics and Astronomy, Ohio University, Athens, Ohio; [2]Advanced Materials Research Institute, University of New Orleans, New Orleans, Louisiana; [3]Department of Physics, King Saud University, Riyadh, Saudi Arabia.

Based on first-principles calculations, Sato et al. predicted that CrGaN has a stable ferromagnetic state with Cr concentration above 2%.[1] In this work, we study the dependence of the structural and magnetic properties on the growth parameters in rf molecular beam epitaxy. We have grown CrGaN films, varying the substrate temperatures from 650 to 700 ^{o}C, the Ga/N flux ratio from 0.65 to 1.0 and the Cr/Ga flux ratio from 0.03 to 0.05. We find the CrGaN properties vary strongly as conditions vary from N-rich to Ga-rich. Nitrogen-rich conditions result in island-like plateau morphology. Metal-rich conditions result in island-like/interconnected plateau morphology, while Ga-rich conditions result in interconnected plateau morphology. We have found that either extreme N-rich or Ga-rich conditions result in poor magnetic properties. On the other hand, a fairly wide range of growth conditions between these two extremes showed good magnetic properties with ferromagnetic behavior up to at least 300K. We discuss the origin of the ferromagnetism in terms of exchange interactions between Cr ions and also the possible effect of ferromagnetic precipitates. In a related study, STM performed at 300K was used to investigate the surfaces of Cr-doped GaN films. We have observed that for low Cr concentration (5% or less), Cr appears to substitute randomly for Ga on the surface. At much higher Cr concentrations such as 20% and after cooling, surface Cr atoms form ordered linear nanostructures along 3-fold symmetry lines. [1] K. Sato, and H. Katayama-Yoshida, Semicond. Sci. Technol. 17, 367 (2002).

4:15 PM FF4.4

Development of UV-LEDS Based on III-Nitride MQWS Grown Along Non-Polar [11-20] Direction. Ramya Chandrasekaran[1], Anirban Battacharyya[1], Adrian Williams[1], Jasper Cabalu[1], Christos Thomidis[1], Theodore D. Moustakas[1], Lin Zhou[2] and David J. Smith[2]; [1]Electrical Engineering, Boston University, Boston, Massachusetts; [2]Department of Physics and Astronomy and Center for Solid State Science, Arizona State University, Tempe, Arizona.

III-Nitride LEDs based on multi-quantum well (MQW) structures, grown along the conventional [0001] (polar) direction; suffer from the quantum confined Stark effect, due to the existence of strong electric fields, arising from the spontaneous and piezoelectric polarizations. In this paper we report the growth and fabrication of UV-LEDs on the R-plane sapphire, which leads to nitride growth along the non-polar [11-20] direction. These LED structures are based on AlGaN MQWs and were designed to emit in the spectra range of 300 to 350 nm. Prior to the growth and fabrication of the LED structures, detailed epitaxial growth and characterization of GaN, AlGaN films and AlGaN MQWs as well as n- and p-type doping studies of GaN and AlGaN films on the R-plane sapphire were carried out. We found that nucleation on the R-plane sapphire is different than that on the C-plane sapphire. Specifically the step of sapphire nitridation (conversion of the surface of Al_2O_3 to AlN by exposure to active nitrogen), which is found to be crucial during growth on the C-plane sapphire, was not necessary during the growth on the R-plane sapphire. Thus nucleation on this sapphire surface occurs by the growth of AlN or GaN buffers. The kinetics of growth of these two buffers was found to influence very significantly the microstructure and opto-electronic properties of the GaN and AlGaN films. Conditions were identified for doping GaN and AlGaN films both n- and p-type. GaN films and AlGaN films with AlN mole fraction 30% were doped with silicon n-type to a level above 1 x10^{19} cm^{-3}. Similarly GaN films were doped p-type with magnesium to a level of 1 x10^{18} cm^{-3} with a mobility of 2 cm^2/Vs. While Mg incorporation during growth along polar direction was found to lead to partial polarity inversion, which inhibits efficient doping, we found that Mg incorporation in films grown along non-polar directions does not affect the efficiency of doping, since polarity inversion is not relevant in this direction of growth. Identical $Al_xGa_{(1-x)}N$/ $Al_yGa_{(1-y)}N$ MQWs were grown on polar (0001) and non-polar (11-20) AlN templates and it was observed that the CL intensity from the MQWs grown along the non-polar direction is more than an order of magnitude higher than the ones grown along the polar direction. Finally, UV-LEDs

structures utilizing the various nitride layers described above were grown and fabricated on non-polar (11-20) AlN templates. These devices were designed for light emission through the sapphire substrate and packaged by flip-chip bonding onto silicon sub-mount.

4:30 PM FF4.5
In Situ Control of Ga-Adsorbate Mediated GaN Growth Mode. Jay Steven Brown[1], Gregor Koblmueller[1,3], Feng Wu[1,2], Robert Averbeck[3], Henning Riechert[3], Pierre Petroff[1] and James Speck[1,2]; [1]Materials, University of California, Santa Barbara, California; [2]JST/ERATO, UCSB Group, University of California, Santa Barbara, California; [3]Corporate Research Photonics, Infineon Technologies AG, Munich, Bavaria, Germany.

Growth of high quality GaN (0001) by rf-plasma molecular beam epitaxy (MBE) requires precise control of the gallium to nitrogen flux ratio. Pit-free GaN films with step-flow morphology are obtained when the Ga flux is sufficient to form macroscopic Ga droplets [1]. First principles total energy calculations have predicted that the most stable Ga-adsorbate configuration in the Ga-rich limit is a laterally contracted bilayer, with equivalent GaN-equivalent coverage of 2.4 MLs [2]. The Ga bilayer on GaN has been proposed to provide a low energy barrier path for N diffusion [3], providing an explanation for the experimentally observed GaN morphology correlation with Ga-flux. We present a study of the GaN morphology evolution as a function of impinging Ga flux for homoepitaxial GaN layers of 8 to 500 nm. We demonstrate GaN growth mode variation from 3D islands, to layer-by-layer, to step-flow with decreasing pit density as the Ga flux is increased systematically from stoichiometry to Ga-droplets conditions. Line-of-sight quadrupole mass spectroscopy (QMS) and reflection high-energy electron diffraction (RHEED) are used to quantify the Ga-adsorbate coverages that mediate transitions in GaN growth mode as a function of Ga flux. We show that 1.0 MLs Ga-adlayer coverage is responsible for the GaN growth mode transition from layer-by-layer to step-flow. We observed that the critical coverage for step-flow GaN growth without pits is 2.4 MLs. To characterize the variation of the Ga-adsorbate coverage as a function of impinging gallium flux in the absence of nitrogen flux, we have investigated Ga desorption from GaN (0001) with simultaneous QMS and RHEED experiments. At fixed substrate temperatures of 638 to 697 C, QMS measurements showed the adsorbate coverage to increase monotonically with the impinging Ga flux up to 2.4 MLs before droplets formation. RHEED was used to characterize the structure of the Ga-adsorbate during desorption, showing a bi-oscillatory behavior [4]. The Ga-adlayer coverage dependence on impinging flux and substrate temperature were analyzed to measure an activation energy of 2.43 eV for the critical transition flux for 1.0 MLs Ga-adlayer coverage. We demonstrate that the in situ techniques of QMS and RHEED provide complementary information that is consistent with the theoretically predicted configuration of the Ga adsorbate on GaN (0001). We present a GaN growth diagram for rf-plasma MBE that includes the flux dependence of Ga-adlayer coverage and the resulting GaN growth mode within each adlayer coverage regime. We conclude that the growth mode dependence we have observed is in accordance with the theoretically predicted nitrogen diffusion barriers on Ga-adlayer surfaces [3]. [1] B. Heying et al., J. Appl. Phys. 88, 1855 (2000); [2] J.E. Northrup et al., Phys. Rev. B 61, 9932 (2000); [3] J. Neugebauer et al., Phys. Rev. Lett. 90, 056101 (2003); [4] C. Adelmann et al., Phys. Rev. B 67, 165419 (2003).

4:45 PM FF4.6
In-Situ Investigation of Surface Stoichiometry During InGaN and GaN Growth by Plasma-assisted Molecular Beam Epitaxy using RHEED-TRAXS. Randy Preston Tompkins, Brenda L. VanMil, Kyoungnae Lee, David Lederman and Thomas H. Myers; Physics, West Virginia University, Morgantown, West Virginia.

Reflection high-energy electron diffraction total-reflection-angle X-ray spectroscopy (RHEED-TRAXS) has been shown to be an effective tool for measuring chemical composition of a growing surface with sub-monolayer sensitivity for InGaAs/GaAs and YBaCuO films. In this technique, the high-energy electrons from the RHEED measurement also excite x-ray fluorescence. Since the RHEED electrons just penetrate the surface, and by using a geometry that measures x-ray takeoff at the total reflection angle, RHEED-TRAX probes primarily the top 20 to 30Å of material. Thus, the surface stoichiometry of layers of GaN and InGaN can be directly probed during growth, including direct measurement of the amount of adsorbed excess Ga or surface ratios of Ga to In. In addition, surface segregation effects of dopants, which can lead to near monolayer coverage in the case of Mg, is directly measurable for the first time. High quality N-polar and Ga-polar GaN grown by MBE is grown under gallium stable conditions, which results in the formation of an excess gallium layer on the surface. There are several models of the amount of Ga in the excess layer. In addition, too much gallium incident on the surface during growth results in gallium droplet formation. Thus, RHEED-TRAX can be used to test predictions and also serve as an in-situ diagnostic to determine the optimal growth regime. InGaN composition is also measured during growth. Sub-monolayer In coverage is measured and is correlated to XRD lattice mearurements. There have been many indirect measurements indicating that near-monolayer coverage of Mg occurs during heavy doping for Ga-polar growth. This model can be tested, and RHEED-TRAX can be used as a diagnostic to work on techniques for altering surface segregation. This work was supported by AFOSR MURI F49620-03-1-0330.

SESSION FF5: Electronic Devices I
Chair: Asif Khan
Tuesday Morning, November 29, 2005
Grand Ballroom (Sheraton)

8:00 AM *FF5.1
GaN HEMTs: An Enabling Technology for Next Generation Solid State Phased Array Applications. Thomas Kazior, Raytheon RF Components, Andover, Massachusetts.

Microwave solid state phased arrays are widely used in both radar and satellite communication systems operating at microwave and millimeter wave frequencies. At present, one of the limitations of these systems is the peak power that can be generated in the T/R module that fits within the element spacing of such an array. Gallium Nitride (GaN) technology offers significant promise in addressing this limitation. MMIC amplifiers based on these devices have the potential to produce ten times more power per element than present GaAs MMIC power amplifiers. Over the last several years tremendous strides have been made in developing and maturing GaN technology. Output power densities exceeding 5W/mm are now routinely achieved, with device operation >50V reported. Device efficiencies (at X-band) of > 60% are also becoming routine. Despite this progress several major challenges remain before GaN becomes a truly viable technology and ready for system insertion. These are reproducibility, reliability, packaging (thermal management) and cost. This talk will present an overview of material and process technology development efforts necesary to address these limitations and enable GaN MMICs to be a reliable, cost effect solution for high power, solid state, phased array applications.

8:30 AM FF5.2
High Power AlGaN/GaN Schottky Barrier Diode with 1000 V Operation. Seikoh Yoshida, Nariaki Ikeda, Jiang Li, Hiroshi Kambayasi, Takahiro Wada and Hironari Takehara; Yokohama R&D Laboratories, The Furukawa Electric Co., Ltd., Yokohama, Kanagawa, Japan.

GaN based electronic devices are very promising for high power, high frequency and high temperature devices due to having the excellent figure of merits. For achieving the high efficiency switching devices such as inverters or converters, not only FETs with a low on-state resistance, but also, a Schottky barrier diode with a high breakdown voltage and a high switching speed are required. The GaN based Schottky barrier diode (SBD) is expected to have a high switching speed. We recently proposed a new structure SBD with dual Schottky metal structures for realizing a low on-voltage. In this paper, we investigated an AlGaN/GaN SBD with a field plate structure for a high breakdown voltage. The AlGaN/GaN heterostructure was grown by MOCVD. The AlGaN buffer was grown on the Si (111) substrate and Al0.25Ga0.75N (25 nm)/ GaN (500 nm) was grown on the buffer layer. The AlGaN/GaN heterostructure without any crack was obtained. After that, a Schottky barrier diode was fabricated using an AlGaN/GaN heterostructure. In order to obtain a high breakdown voltage, a gate field plate structure was used. SiO2 was formed on the AlGaN layer using a plasma chemical vapor deposition. The isolation of SBD was carried out using a dry-etching technique. Furthermore, using the SiO2 film, the field plate structure was formed on the gate area. That is, the Schottky electrode of Ni/Au was partially deposited on the SiO2 film towards the ohmic region. The length of field plate structure was also changed to investigate the effect. Ti/Al-silicide was used for an ohmic electrode of SBD. The contact resistance of ohmic electrodes was 8E-6 ohmcm2. The current-voltage characteristics of an AlGaN/GaN SBD were measured. The reverse breakdown voltage of the diode with a size of 0.2 mm x 0.4 mm was also over 1000 V and the reverse leakage current was below 1E-6 A/mm. The maximum operation current of the diode with a large size of 5 mm x 5 mm was 10 A and the reverse breakdown voltage was over 400 V. The switching time of the diode was about 3 ns. A higher switching speed was confirmed. Furthermore, we fabricated the DC-DC converter using these diodes.

8:45 AM FF5.3
Effects of the high-refraction index SiNx passivation on AlGaN/GaN HFETs with a very low gate-leakage current.

Hiroshi Kambayashi, Takahiro Wada, Nariaki Ikeda and Seikoh Yoshida; Yokohama R&D Laboratories, The Furukawa Electric Co., Ltd., Yokohama, Kanagawa, Japan.

AlGaN/GaN heterojunction field effect transistors (HFETs) can be operated under high-power, high-frequency, and high-temperature conditions. In order to perform a low loss switching device, it is required to reduce the leakage current of HFETs. Recently, it has been discussed that the leakage current of the gate can be reduced by the passivation film such as SiO2 or SiNx. However, the HFETs using these passivation films have several problems. In the case of using an SiO2, the current collapse often occurs based on the electron traps due to the AlGaN surface states. On the other hand, in the case of an SiNx film, the current collapse can be suppressed, although the leakage current of HFET is increased. However, this leakage current has to be lowered to obtain a low loss switching device. In this paper, we investigated the stress effects of the passivation film on AlGaN/GaN HFETs in order to suppress the gate-leakage current and the current collapse of HFETs. A heterostructure of an undoped AlGaN (20nm) / GaN (750nm) / AlGaN buffer / Si (111) substrate was grown using a metal organic chemical vapor deposition (MOCVD) method. Three different types of passivation films were deposited on the AlGaN surface using a plasma enhanced chemical vapor deposition (PECVD) method. These films were low-refraction index (1.85) SiNx, high-refraction index (2.02) SiNx, and SiO2, respectively. We measured the value of the stress for these films. As a result, these values were 5.0E9 dyn/cm2 for a low-refraction index SiNx, 2.2E9 dyn/cm2 for a high-refraction index SiNx, and 2.5E9 dyn/cm2 for an SiO2, respectively. The stress type of both SiNx films was tensile, and that of SiO2 was compressive. From these results, the absolute value of the stress of the high-refraction index SiNx was the lowest. Furthermore, using these three types of passivation films, the HFETs were fabricated to compare the gate-leakage current and the current collapse of HFET. The gate width was 200μm and the gate length was 2μm. When the gate bias was applied to -5V, the gate-leakage current of the HFET passivated by the high refraction index SiNx was 6.4E-8 A/mm. This value was about 3 orders of magnitude lower than that of using the low-refraction index SiNx, and about 2 orders of magnitude lower than that of using the SiO2. In addition, the current collapse of this HFET also drastically decreased. We thus confirmed the relationship between the stress of passivation film and gate-leakage current, and that the low stress SiNx film with a high-refraction index is very promising for a passivation film of a high performance AlGaN/GaN HFETs.

9:00 AM FF5.4
Piezo-electric stress and self-heating effects in the AlGaN/GaN HFET probed by micro-Raman spectroscopy.
Andrei Sarua[1], Hangfeng Ji[1], Martin Kuball[1], Michael J. Uren[2], Trevor Martin[2], K. P. Hilton[2] and R. S. Balmer[2]; [1]Physics, University of Bristol, Bristol, United Kingdom; [2]QinetiQ Ltd., Malvern, Worcs, United Kingdom.

Performance and reliability of high-frequency high-power AlGaN/GaN heterostructure field effect transistors (HFET) are affected by the presence of high electrical fields during device operation. Not only do the high electric fields result in significant Joule-Lenz heat generation in the narrow source-drain region of the devices, but can also produce significant amounts of piezo-electric stress in the devices since GaN is a piezo-electric material. Using spatially resolved micro-Raman spectroscopy we illustrate the presence of significant piezo-electric stress in different parts of the device structure under high bias conditions. Using confocal microscopy and measuring from the back through the transparent SiC substrate allowed unique access to the whole device area. Significant piezo-electric stress variations were detected over the device area, dependent on bias load and device layout. In particular, areas in the gate-drain gap and underneath the drain contact are affected. By taking into account piezo-electric field contributions device temperatures were obtained for devices operated under high bias conditions, including areas underneath the device contacts. The accuracy of this method was demonstrated using the temperature dependence of the E_2(high) and A_1(LO) phonon modes of GaN and as well as of the Stokes-Antistokes scattering intensity ratio. Modeling of the temperature and electric field profile in the device structure using finite difference code and drift diffusion models was performed and compared to the experimental data. The illustrated method confirmed the direct link between electric field distribution and observed piezo-electric stress/temperature profile opening the path for studying the electric field distribution using optical spectroscopy.

SESSION FF6: InN
Chair: Joan Redwing
Tuesday Morning, November 29, 2005
Grand Ballroom (Sheraton)

9:15 AM *FF6.1
Growth Studies and Nanoscale Strain Profiles of InN Quantum Dots. Olivier Briot, Sandra Ruffenach and Bernard Gil; GES, CNRS, Montpellier, France.

Nitride semiconductors have been at the center of semiconductor research in the last decade. However, indium nitride is still poorly known, due to its growth difficulty, and its properties are still the subject of passionate debate. Still, it is clear that it is a very promising material for telecommunication optoelectronics and hyperfrequency/terahertz applications. In particular, nanostructures based on InN are extremely interesting, by combining a small bandgap, the incredible efficiency of nitride semiconductors and the tunability of quantum dots. In this paper, we present the latest advances in the growth and optical properties of InN quantum dots grown onto GaN. The optical properties of the dots will be compared to those of InN thin films, and we will show that the thermal behaviour of InN dots is far superior. Using TEM and synchrotron radiation diffraction, we will analyze the strain state of InN dots at the nanometer scale, along the growth axis of the dots. These results, combined with the thermodynamical analysis of the growth data, will allow us to demonstrate that the dot growth mechanism is not the usual Stranski-Krastanov mode, but is more related to the BCF (Burton - Cabrera - Franck) model.

9:45 AM FF6.2
Properties of InN grown by High-Pressure CVD.
Vincent Woods[1], Mustafa Alevli[1], Ute Haboeck[3], Hun Kang[2], Jayantha Senawiratne[1], Martin Strassburg[1,2], Ian T. Ferguson[2], Axel Hoffmann[3] and Nikolaus Dietz[1]; [1]Physics & Astronomy, Georgia State University, Atlanta, Georgia; [2]Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, Georgia; [3]Institut fuer Festkoerperphysik, Technische Universitaet Berlin, Berlin, Germany.

Group III-nitride material systems (e.g. AlN-GaN-InN) have generated considerable interest for use as the basis for advanced optoelectronic device structures. Fabrication of multi-tandem solar cells, high-speed optoelectronics and solid state lasers operating in the higher energy wavelengths have been made possible using (Ga1-y-xAlyInx)N heterostructures due to their robustness against radiation and the wide spectral application range. So far, he growth of indium rich (In1-xGax)N films and heterostructures remains a challenge, primarily due to the large thermal decomposition pressures in indium rich group III-nitride alloys at the optimum growth temperature. As reported in this contribution, high-pressure chemical vapor deposition (HPCVD) overcomes the limitations, enabling the growth of InN and indium rich group III-nitride alloys. This high pressure approach allows InN growth at temperatures as high as 1150 K for reactor pressures around 15 bar, which is a major step forward towards the production of indium rich heterostructures, providing a closer match to the ideal processing temperatures of (Ga1-y-xAlyInx)N. Real-time optical characterization techniques are applied to study and control the gas phase kinetics and surface chemistry processes during the growth process. The structural analysis by XRD and Raman indicates single phase for ammonia to TMI ratio down below 500. For ammonia to TMI ratio below 200, multiple phases with sharp XRD pattern are observed. The optical InN layer characterization indicates that the shift of the absorption edge from 1.85 eV down below 0.6 eV is caused by a series of absorption centers that appear as the indium to nitrogen stoichiometry varies. This contribution will provide results from the real-time optical characterization of InN and will correlate the process parameter to results obtained by XRD, Raman spectroscopy and optical spectroscopy, in order to asses the film quality.

10:15 AM FF6.3
Comparison Between N- and In- Polarity InN/InGaN MQWs Structures Grown by RF-MBE. Songbek Che[1,2,3], Tomoyasu Mizuno[1], Takurou Shinada[1], Yoshihiro Ishitani[1,2,3] and Akihiko Yoshikawa[1,2,3]; [1]Department of E&M Engineering, Chiba University, Chiba, Japan; [2]Center for Frontier Electronics and Photonics, Chiba University, Chiba, Japan; [3]InN-Project as a CREST-program of JST, Chiba University, Chiba, Japan.

InN is attracting strong interest in its unique properties such narrow bandgap energy as 0.6-0.7eV, which indicates the potential application of InN-based III nitrides in near-infrared photonic devices. Up to present, we have studied the InN-based quantum well structures with an aim of the photonic device application. The InN/InGaN multi-quantum wells (MQWs) structure is a candidate for the active layer of the devices. In this study, we fabricated the InN/$In_{0.7}Ga_{0.3}N$ MQWs in each polarity by RF-MBE and investigated the polarity dependence of them on their structural properties. Polarity control is quite important especially for the growth of InN. We already reported that the epitaxy temperature of InN in MBE could be about 100 deg higher in N-polarity growth compared to that in In-polarity. Higher growth temperatures are believed to be preferable to obtain high

crystalline quality. Actually, best quality InN films could be grown in N-polarity growth regime in our group so far. Moreover, we could successfully grow the N-polarity InN/$In_{0.7-0.8}Ga_{0.3-0.2}N$ MQWs, which showed good interface quality and near infrared emission at RT. On the other hand, in the case of the In-polarity InN growth, its growth temperature was limited to approximately 500°C, which seems to be a disadvantage in obtaining high crystalline quality. However, in general, the nitride epitaxy in cation-polarity provides relatively smooth surface morphology and good crystalline quality than that in N-polarity. Therefore, it is mentioned that there is a possibility for the growth of the In-polarity InN/InGaN MQWs structures with good crystalline quality by optimizing their growth condition in spite of its low critical growth temperature. In this study, in order to investigate how the polarity control affects the InN-based MQWs growth, the InN/$In_{0.7}Ga_{0.3}N$ MQWs in each polarity were grown by RF-MBE. In the case of the N-polarity growth, the MQWs were grown at 550°C on MBE-grown GaN templates which were grown on the nitrided sapphire substrates. On the other hand, for the In-polarity growth, growth temperature of the MQWs was 450°C and MOCVD-grown GaN templates were used. The MQWs consisted of GaN underlayers, 20 periods QWs and $In_{0.7}Ga_{0.3}N$ cap layer (20nm). In the PL measurement at RT, strong emission at around 2μm was observed from the N-polarity InN(1nm)/$In_{0.8}Ga_{0.2}N$ (6nm) MQWs sample. XRD 2θ-ω scans were measured for each polarity InN/InGaN MQWs. Clear satellite peaks up to 3rd order were observed in both samples which indicated that good interface quality was obtained in these structures. It was also noticed that full-width at half-maximum of 0 and -1 order peaks were estimated to be 680arcsec, 496arcsec for N-polarity InN(8nm)/$In_{0.7}Ga_{0.3}N$(8nm) MQWs and 222acsec, 330arcsec for In-polarity InN(4nm)/$In_{0.7}Ga_{0.3}N$(7nm) MQWs. These results indicated that despite lower growth temperature, the InN/InGaN MQWs with superior interface quality could be obtained in the In-polarity growth.

10:30 AM FF6.4
Influence of Nitrogen Species on InN Grown by PAMBE. P. A. Anderson[1,3], D. Carder[2,3], R. J. Reeves[2,3] and S. M. Durbin[1,3]; [1]Electrical & Computer Engineering, University of Canterbury, Christchurch, New Zealand; [2]Physics, University of Canterbury, Christchurch, New Zealand; [3]MacDiarmid Institute for Advanced Materials and Nanotechnology, Christchurch, New Zealand.

Radio frequency inductively coupled plasmas are now the preferred active nitrogen source for the molecular beam epitaxy growth of group-III nitrides. The species emitted from RF sources typically consist of a combination of various molecular, atomic and ionic species. These species have been shown to have a profound effect on GaN electrical properties, [1] which provides motivation for exploring whether InN growth behaves similarly. The two methods which have previously been used to quantify species produced by RF sources are line of sight mass spectroscopy, [1] and monitoring of the optical emission from the sources. [2] In this study we investigate how the optical, electrical, and structural properties of single crystal InN thin films correlate with active nitrogen species. The optical emission from an Oxford Applied Research model HD-25 nitrogen plasma source was monitored between 500 - 900 nm for RF powers ranging from 65 - 400 W and flow rates from 0.65 - 1.9 sccm. This region of the spectrum contains strong emission peaks from both atomic nitrogen and 1st-positive series excited molecular nitrogen which are known to be the two dominant species produced by RF sources. It is found that for low RF powers and high nitrogen flow rates comparatively more 1st-positive series excited molecular nitrogen is produced. A series of InN films were grown on sapphire substrates with GaN buffer layers at various active molecular to atomic flux ratios. The mobility of the films was found to increase with increasing active molecular content up to a maximum of 390 $cm^2/V\cdot s$ for growth at 450°C. Accordingly the carrier concentration was found to decrease with increasing active molecular species to a minimum n-type concentration of 5×10^{18} cm^{-3}. Photoluminescence studies revealed strong emission from all films between 0.65 - 0.7 eV. The intensity of luminescence was found to be brightest for the films grown with high relative molecular flux. Reflection high energy electron diffraction (RHEED) was used to monitor the lattice relaxation as the InN film grew on the mismatched GaN layer. It was observed that for high relative active molecular flux rates the film would not relax fully until it was approximately 30 nm thick. In contrast, films grown under a low relative active molecular flux were found to relax fully within the first several nanometres of growth. These observations confirm that the active nitrogen species can have a significant effect on InN film growth and electronic properties, and provides motivation for operating RF sources at low power where the relative production of 1st-positive series molecular nitrogen is greatest. [1] A. J. Ptak, M. R. Millecchia, T. H. Myers, K. S. Ziemer, and C. D. Stinespring, Appl. Phys. Lett. 74, 3836 (1999). [2] See, for example, A. Georgakilas, H. Min, and P. Komninou, Nitride Semiconductors: Handbook on materials and devices. Weinheim, Germany: Wiley-VCH, 2003, pp 107-191.

10:45 AM *FF6.5
Carrier Recombination, Relaxation, and Transport Dynamics in InN. Fei Chen[1], Alexander N Cartwright[1], Hai Lu[2] and William J Schaff[2]; [1]Department of Electrical Engineering, University at Buffalo, State University of New York, Amherst, New York; [2]Department of Electrical and Computer Engineering, Cornell University, Ithaca, New York.

Knowledge of the carrier recombination, relaxation, and transport rates in InN materials is essential for evaluation of the potential for photonic and electronic applications. Ultrafast time-resolved optical spectroscopy provides access to these carrier dynamics in semiconductors and provides some information that can not be accessed electronically. Specifically, in this work femtosecond transient transmission and transient grating techniques, along with the extracted rates, will be presented. The femtosecond transient transmission measurements provide information such as carrier recombination lifetime and the carrier thermalization time of InN. Specifically, we observed a fast initial hot carrier cooling followed by a slower recombination process. At short times after pulsed excitation, modeling of the observed relaxation suggests that the dominant energy relaxation process is longitudinal optical phonon scattering modified by a strong hot phonon effect at room temperature. An inverse proportionality between the carrier lifetime and the free electron concentration was found and suggests that the donor-like defects or impurities may stimulate a formation of non-radiative recombination centers. While the observed decay times at room temperature are attributed to a defect related nonradiative recombination channel, at low temperature (20 K) they are well explained by a dominating radiative interband recombination. For high-quality samples, we find the radiative lifetime increases proportional to $T^{3/2}$ as theory predicts when a k-selection rule holds. This suggests that the radiative band-to-band transition accounts for the observed infrared photoluminescence over the entire temperature. Furthermore, we report the measurements of in-plane carrier transport and hole mobility of an InN epilayer through time-resolved transient grating spectroscopy by using femtosecond pulses at 800 nm and ~1900 nm for grating writing and probing, respectively. The ambipolar diffusion coefficient D_a = 2.0 cm^2/s and hole mobility μ_h = 39 cm^2/Vs at 300 K near the InN surface were determined by monitoring the transient grating kinetics at various grating periods. In addition, we observed a decrease of hole mobility and carrier lifetime at the internal epilayer/buffer interface in comparison with those at the free surface, suggesting a faster carrier capture rate to the defect states and a more efficient defect and impurity scattering mechanism.

11:15 AM FF6.6
Electron Transport Properties of InN. Rebecca E. Jones[1,2], Sonny X. Li[1,2], Leon Hsu[3], Kin Man Yu[2], Wladek Walukiewicz[2], Joel W. Ager[2], Eugene E. Haller[1,2], Hai Lu[4] and William Schaff[4]; [1]Materials Science and Engineering, University of California, Berkeley, Berkeley, California; [2]Materials Sciences Division, Lawrence Berkeley National Laboratory, Berkeley, California; [3]General College, University of Minnesota, Minneapolis, Minnesota; [4]Electrical and Computer Engineering, Cornell University, Ithaca, New York.

The recent explosion of interest in InN has spurred a research effort motivated by potential optoelectronic and electronic device applications such as high-efficiency solar cells and high-frequency transistors. Much of the current research focuses on understanding the unusual charge transport properties of InN. These properties are caused by formation of an electron surface accumulation layer and a remarkable proclivity of this material for n-type conductivity [1]. The need to properly account for the contribution of surface electrons to the total conductivity and the existence of many possible sources of electrons makes an analysis of the transport properties of InN especially daunting. Failure to recognize the full complexity of the electron transport has led to a large spread in the values of electron concentrations and mobilities reported in the literature. Even intentionally doped samples grown under similar conditions can have distinctly different reported mobilities for the same carrier concentrations. To address this issue, we have investigated transport properties of MBE-grown films irradiated with high-energy particles. We have shown recently that irradiation of InN with 2 MeV He^+ ions provides a reproducible method to control the electron concentration across a broad concentration range, from low-10^{18} cm^{-3} to mid-10^{20} cm^{-3} [2]. A clear advantage of such "defect doping" is that the electron concentration may be varied widely by sequentially irradiating the same samples. This approach eliminates the possible variations in other factors affecting the electron mobility. Our experimental results are compared with calculations of the electron mobility that are based on Kane's model of the electronic structure of narrow gap semiconductors. The model takes into account the nonparabolic dispersion relation and the admixture of the p-like valence band and the conduction band wave functions. Our calculations show that in the entire available electron concentration range, the room temperature electron mobility is limited by scattering

from ionized defects. In samples irradiated with high-energy particles, the mobility is well-explained assuming an effective compensation ratio of k = 0.6. Rapid Thermal Annealing (RTA) of irradiated samples results in a reduction of electron concentration and a drastic, five-fold increase in electron mobility. The compensation ratio in the annealed samples approaches k = 0.2, which is close to the compensation ratios found in the highest-mobility InN films intentionally doped with Si. This work is supported by the U.S. Department of Energy under contract number DE-AC02-05CH11231. [1] I. Mahboob, et al., Phys. Rev. Lett. **92**, 036804 (2004). [2] S.X. Li, et al., Phys. Rev. B **71**, 1(R), (2005).

11:30 AM FF6.7
Evidence of p-Type Conductivity in Mg-Doped InN.
Kin Man Yu[1], Rebecca E. Jones[1,2], Sonny X. Li[1,2], Wladek Walukiewicz[1], Joel W. Ager[1], Eugene E. Haller[1,2], Hai Lu[3] and William J. Schaff[3]; [1]Materials Sciences Division, Lawrence Berkeley National Laboratory, Berkeley, California; [2]Materials Science and Engineering, University of California, Berkeley, Berkeley, California; [3]Electrical and Computer Engineering, Cornell University, Ithaca, New York.

Improvements in the growth of InN and the discovery of its low bandgap (∼0.7 eV) have created great interest in the material's potential use in optoelectronic devices, such as high efficiency solar cells [1, 2]. In order to realize these applications, the ability to fabricate both p-type and n-type InN is essential; however, only n-type InN has been achieved to date. InN has an extreme propensity for n-type activity and surface electron accumulation [3], with "bulk" free electron concentrations over 10^{17} cm^{-3} and surface concentrations in the low 10^{20} cm^{-3}, due to the pinning of the surface Fermi level high in the conduction band [3]. We have used electrolyte-based capacitance-voltage (CV) and Hall effect measurements on as-grown and high-energy-particle irradiated samples to demonstrate the first evidence of p-type activity in Mg-doped InN. Epitaxial InN films have been grown with Mg concentrations of 10^{20} to 10^{21} cm^{-3}, as measured by SIMS. The films exhibit net n-type conductivity by Hall effect measurements, but have electron mobilities below 100 cm^2/V s. Also, in striking contrast to undoped InN grown under similar conditions, which generally has strong band edge photoluminescence (PL), no PL has been detected in the Mg-doped samples. The depth distribution of the net charge was measured using the CV technique. In Mg-doped samples there is a very thin (<5 nm), high concentration n-type layer at the surface of the material, followed by a region interpreted to be p-type polarity, with a charge concentration in the mid-10^{19} cm^{-3}. No such type reversal has been observed in undoped samples where both the surface accumulation layer and the bulk show n-type behavior. The net charge distribution is consistent with the low electron mobility in the Mg-doped samples; the charge transport is fully determined by the conductivity in the thin, high-electron-density surface accumulation layer. Further evidence for p-type bulk material is demonstrated using high-energy irradiation with He^+ ions, which, as we have previously shown, generates a net number of donor-type defects [4]. Thus, at sufficiently high irradiation doses, p-type material should turn n-type. Indeed we find that irradiation with He^+ doses higher than 2.1x10^{15} ions/cm^2 converts Mg-doped InN into n-type conducting material throughout. This is evidenced by CV measurements of irradiated samples, where type reversal in the depth profiles is not observed. Also the irradiation-induced p- to n-type conversion of the bulk material causes an unusual effect; the damage leads to a large increase of the electron concentration and the electron mobility. This work is supported by the U.S. Department of Energy under contract number DE-AC02-05CH11231. [1] V.Yu Davydov, et al., Phys. Status Solidi B **229**, R1 (2002). [2] J. Wu, et al., Appl. Phys. Lett. **80**, 3967 (2002). [3] I. Mahboob, et al., Phys. Rev. Lett. **92**, 036804 (2004). [4] S.X. Li, et al., Phys. Rev. B **71**, 1(R), (2005).

SESSION FF7/EE5: Joint Session: Nitride Materials for Devices
Chair: Christian Wetzel
Tuesday Afternoon, November 29, 2005
Grand Ballroom (Sheraton)

1:30 PM *FF7.1/EE5.1
III-N Epitaxial Growth for Nitride Devices.
Russell Dupuis, Theodore Chung, Wonseok Lee, Peng Li, Jae Limb, Jae-Hyun Ryou and Dongwon Yoo; Center for Compound Semiconductors, School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, Georgia.

Various GaN-based device structures were grown on (0001) sapphire, 6H-SiC, and "bulk" GaN substrates by metalorganic chemical vapor deposition. The device structures of this talk consist of both majority and minority carrier devices, namely, InGaN green-emitting LEDs, $p-i-n$ rectifiers, AlGaN-GaN heterojunction field-effect transistors, and heterojunction bipolar transistors. These structures are grown by MOCVD using TMGa, TEGa, TMAl, TMIn and NH_3 precursors. This talk will compare the performance of these various device structures on the three different substrates. The material properties of the structures were characterized by photoluminescence (PL), optical transmittance, X-ray diffraction (XRD), atomic force microscopy (AFM), transmission electron microscopy (TEM), sheet resistance mapping, and triple-axis ω-2θ scans by XRD on an (002) and (102) reflection planes. AFM measurements on the surfaces of these devices typically show atomic steps and localized defects due to dislocations with the RMS roughness values for the three substrates varying sapphire > SiC > GaN. The green LEDs show relatively narrow PL emission at wavelengths ∼540nm. Major performance characteristics of the rectifier, such as the on-state resistance, breakdown voltage, and reverse bias leakage current, are compared depending on the substrate and the passivation scheme employed. Under optimized conditions, $p-i-n$ diodes with >500V reverse bias breakdown and an on-resistance less than 3 mΩ·cm^2 were achieved. HFETs grown on SiC show high mobilities and sheet charge with μ=1,900 cm^2/V-s and n_s=1.3x10^{13} cm^{-2} with a sheet resistance ∼240 Ω/sq. Nitride *npn* HBTs have been grown with graded InGaN emitter and base layers. Base contact resistance and base access etching still need to be developed. Our best InGaN HBTs to date exhibit DC beta ∼6, limited by the difficulty in achieving high base current injection due to a high base contact resistance.

2:00 PM FF7.2/EE5.2
MOVPE growth of AlInN based devices.
Armin Dadgar[1], Juergen Blaesing[1], Christoph Hums[1], Martin Neuburger[2], Ingo Daumiller[3], Mike Kunze[3], Hartmut Witte[1], Andre Krtschil[1], Annette Diez[1], Erhard Kohn[2] and Alois Krost[1]; [1]Fakultaet fuer Naturwissenschaften, Institut fuer Experimentelle Physik, Otto-von-Guericke-Universitaet Magdeburg, Magdeburg, Germany; [2]Department of Electron Devices and Circuits, University of Ulm, Ulm, Germany; [3]MicroGaN GmbH, Ulm, Germany.

The group III-nitride ternary compound AlInN has some outstanding properties with a potential use for novel transistor and light emitting devices. First of all AlInN can be grown lattice matched to GaN with an In-concentration of 18%. The high index jump of this Al-rich compound to GaN makes it interesting for crack-free bragg reflectors to be used in RC-LED or VCSEL devices. Secondly, the large difference in the spontaneous polarization of AlInN and GaN leads to a large polarization charge which can be increased or decreased by tensily or compressively grown AlInN on GaN, respectively. By this high 2DEG sheet charge densities well above 2x10^{13} cm^{-2} can be easily achieved and for In concentrations above 32% it is expected that a p-channel will be formed at the GaN / AlInN heterojunction. We will present a detailed study on the MOVPE growth conditions on In segregation during AlInN growth. We have achieved high-current FET devices with DC currents in excess of 1.8 A/mm and 2DEGs above 3x10^{13} cm^{-3}. By systematically increasing the In-content the 2DEG density decreases. Layers with high In-content AlInN to induce holes at the GaN / AlInN heterojunction will be presented. Additionally, we show details and difficulties on the growth of AlInN / GaN VCSEL structures with reflectivities exceeding 99%.

2:15 PM FF7.3/EE5.3
Spontaneous Compositional Superlattice and Band Gap Reduction in Si-doped $Al_xGa_{1-x}N$ Epilayers.
Min Gao[1], Yong Lin[1], Shawn Bradley[1], Jeonghyun Hwang[2], William Schaff[2], Steven Ringel[1] and Leonard Brillson[1]; [1]the Ohio State University, Columbus, Ohio; [2]Cornell University, Ithaca, New York.

Spontaneous long range ordering has been extensively studied in epitaxial compound semiconductors, especially in III-V alloys. One major driving force of such high interest is that the spontaneous ordering may significantly modify the band gap and other electronic properties. In this paper, we report a systematic study of spontaneous long range ordering in $Al_xGa_{1-x}N$ thin films across the full alloy series as well as its effect on near band edge (NBE) recombination and optical emission. We used atomic resolution scanning transmission electron microscopy (STEM), high resolution x-ray diffraction (HRXRD) and low temperature cathodoluminescence spectroscopy (CLS), with emphases on the nature of the ordering structure, its dependences on AlN mole fraction and growth temperature, and its influence on structural and optical properties. The $Al_xGa_{1-x}N$ samples were grown by molecular beam epitaxy at 800°C under group III-rich condition. The observed spontaneous ordering was along *c*axis (growth direction) with a period that varied from 7 to 13 monolayers. We used atomic resolution Z-contrast imaging and high spatial resolution energy dispersive x-ray spectroscopy (EDS) to probe the distribution of Al and Ga and established the first direct evidence that the spontaneous ordering was atomic compositional superlattice in which the composition varied in an approximate sinusoidal pattern. Quantitative HRXRD and STEM results displayed both ordering and

phase separation that depended systematically on Al mole fraction. At low Al concentration (x ≤ 0.50), pronounced phase separation predominated with relatively weak ordering degree. High Al concentration (x ≥ 0.65) enhanced the spontaneous ordering and suppressed the phase separation dramatically. The ordering period decreased slightly with increasing AlN mole fraction. In addition, it was found that lower growth temperature resulted in stronger ordering degree at low Al concentration and shorter ordering period. Furthermore, micro-CLS measurements displayed considerable energy reductions of NBE emissions in the ordered $Al_xGa_{1-x}N$ films. Strong correlations were observed between the energy reduction of NBE emission and the ordering degree revealed by HRXRD and STEM, indicating ordering-induced band gap reduction ranging above 500 meV. To a first approximation, these results indicate that the effective band gap is determined by the lowest band gap in the compositionally ordered superlattice, i.e., that the superlattice acts as a sink for recombination. Our results show that the ordering competes with phase separation in reducing the overall system energy, with the stabilization of the ordering at high Al concentration attributed to the slow diffusion mobility of Al. This work demonstrates that the atomic ordering has significant implications for Al-rich $Al_xGa_{1-x}N$ devices. Possible applications of such spontaneous superlattice will be discussed.

3:30 PM FF7.4/EE5.4

Structural, Optical, and Magnetic Behavior of in-situ Doped, MOCVD-Grown Ga(1-x)Mn(x)N Epilayers and Heterostructures. Martin Strassburg[1,2], William E. Fenwick[1], Matthew Kane[1,3], Ali Asghar[1], Shalini Gupta[1], Hun Kang[1], Christopher Summers[3], Nikolaus Dietz[2], Wolfgang Gehlhoff[4], Axel Hoffmann[4] and Ian T. Ferguson[1]; [1]Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, Georgia; [2]Department of Physics and Astronomy, Georgia State University, Atlanta, Georgia; [3]School of Materials Science and Engineering, Georgia Institute of Technology, Atlanta, Georgia; [4]Institute of Solid State Physics, Technical University of Berlin, Berlin, Germany.

Dilute magnetic semiconductors (DMS) show promise as materials that can exhibit ferromagnetism at room temperature (RT). However, the nature of ferromagnetism in this material system must be well understood in order to allow intelligent design of RT spintronic devices. This work investigates the magnetic properties of the as-grown films and the effect of Mn incorporation on crystal integrity and device performance. Ga(1-x)Mn(x)N films were grown by MOCVD on c-plane sapphire substrates with varying thickness and Mn concentration. Homogenous Mn incorporation throughout the films was verified with Secondary Ion Mass Spectroscopy (SIMS), and no macroscopic second phases (MnxNy) were detected using X-ray diffraction (XRD). Superior crystalline quality in the MOCVD-grown films relative to Mn-implanted GaN epilayers was confirmed via Raman spectroscopy. SQUID measurements showed an apparent room temperature ferromagnetic hysteresis with saturation magnetizations greater than 2muB/Mn in some cases, but the muB per Mn contribution decreases with increasing Mn incorporation. Similarly, a marked decrease in the magnetization was observed with annealing and silicon doping, as well as in post-growth annealed Mg-codoped samples. The observed decrease in muB per Mn with increasing Mn concentration is explained by Raman spectroscopy results, which show a decrease in long-range lattice ordering and an increase in nitrogen vacancy concentration with increasing Mn concentration. Magnetic and electron-spin paramagnetic resonance (EPR) data also show that the position of the Fermi level relative to the Mn2+/3+ level is the determining factor in magnetization. Vibrating Sample Magnetometry (VSM) will be used to further investigate the magnetic properties and magnetic anisotropy of the samples. Light emitting diodes (LEDs) containing a Mn-doped active region have also been produced. Devices were fabricated with different Mn-doped active layer thicknesses, and I-V characteristics show that the devices become more resistive as thickness of the Mn-doped active layer increases. The magnetic and structural properties observed in this work will be used in conjunction with characteristics and magneto-optical of the Mn-containing devices to discuss the theoretical models of ferromagnetism in Ga(1-x)Mn(x)N.

3:45 PM FF7.5/EE5.5

Fe-Centers in GaN as Candidates for Spintronics Applications. Enno Malguth[1], Axel Hoffmann[2], Matthew Phillips[1] and Wolfgang Gehlhoff[2]; [1]Microstructural Analysis Unit, University of Technology, Sydney, New South Wales, Australia; [2]Institute of Solid-State-Physics, Univerity of Technology, Berlin, Germany.

For the potential use of iron doped GaN as a material for spintronic applications, it is of great importance to know the exact energetic positions of the electronic states of the Fe ions in the bandgap. Another crucial issue is the charge state in which the iron is present. In order to investigate these issues a set of approximately 400μm thick, freestanding HVPE grown GaN:Fe crystals with different Fe-concentration levels ranging from $2{\cdot}10^{16}$ cm^{-3} to $2{\cdot}10^{20}$ cm^{-3} was studied. The methods used for investigation were: photoluminescence (PL), transmission, photoluminescence excitation (PLE) and electron paramagnetic resonance (EPR). The fact that the samples are freestanding enabled us to carry out the optical experiments with both parallel and perpendicular polarization, relative to the c-axis. We were able to establish a consistent picture of the different charge states present in the samples and their respective term schemes including fine structure. The presence of Fe^{2+}, Fe^{3+} and Fe related defect-complexes with dependance on the iron concentration was identified. The positions of the electronic states in the bandgap were determined not only for the 3+ but also for the 2+ charge state. The intra-center Fe^{2+} transition ($^5E \rightarrow ^5T_2$) observed here for the first time and the conduction band were previously believed to be degenerate. A multiple splitting of all of the Fe^{2+} and Fe^{3+} states was observed. The reason is the distortion of the trigonal crystal field along the c-axis resulting in c_{3v} symmetry. Particularly for the $^5E \rightarrow ^5T_2$ transitions of the Fe^{2+} could a complex absorption structure be resolved. From the lines' respective predominant polarization and temperature behavior, most of the observed lines could be assigned to ^5E and $^5T_2$ sublevels which are split in the trigonal crystal field.

4:00 PM FF7.6/EE5.6

Highly Insulating Non-polar a-GaN/AlGaN Films and Heterojunctions over r-Sapphire. Z. Chen, Jinwei X. Yang and M. Asif Khan; Electrical Engineering, University of South Carolina, Columbia, South Carolina.

Several groups in the past, including ours, have reported on non-polar light emission devices using a-plane GaN pn-junctions over r-plane sapphire substrates. These devices used GaN or AlGaN buffer layers that were deposited either by conventional MOCVD or the selective area lateral epitaxy approaches. In either case the as deposited layers were highly n-doped. This made them unsuited for the deposition of GaN/AlGaN layers or heterojunctions for the electronic devices. It also precluded a systematic study of electron transport in non-polar a-plane oriented films where such transport can possibly be lateral direction dependant. Now using a novel migration enhanced metalorganic chemical vapor deposition (MEMOCVD) approach we have for the first time succeeded in depositing highly insulating layers of a-GaN and a-GaN-AlGaN heterojunctions over r-plane sapphire substrates. These MEMOCVD growths were carried out at 40 torr and 1050 C and trimethyl aluminum (TMA), trimethyl gallium (TMGa) and NH3 were used as the precursors. The TMA and the TMG precursors and NH3 were alternately supplied to the growth chamber as 6 sec long alternating pulses. The pulse overlap was avoided to minimize pre-reaction which invariably leads to degraded morphology. Both undoped and silicon doped structures were deposited and their structural, electronic and optical properties were measured. The MEMOCVD approach resulted in highly insulating GaN/AlGaN buffer layers. It was also possible to control their n-type conductivity by silicon doping using SiH4 as the dopant. The electronic transport in the different crystal directions was studid using cross oriented TLM and Hall patterns. Our results show that the a-GaN layers can be doped n-type with carrier concentration as high as 2x1019cm-3 still maintaining a carrier mobility as high as 40 cm2/V-sec. In this paper we will discuss the growth details and the n-type conductivity of single layers and GaN-AlGaN heterojunctions. Some preliminary results of fabricating non-polar transistors will also be presented.

4:15 PM FF7.7/EE5.7

Realization of high-crystallinity a-plane GaN grown on r-plane sapphire substrate for high-performance light-emitting device. Yoshizane Okadome, Youshuke Tsuchiya, Hiroko Furukawa, Kentarou Nagamatsu, Akira Honshio, Motoaki Iwaya, Satoshi Kamiyama, Hiroshi Amano and Isamu Akasaki; Meijo University, Nagoya, Aichi-prefecture, Japan.

Although visible short-wavelength light-emitting diodes (LEDs) based on group III nitrides have been commercialized, the performance of these LEDs in longer wavelength regions, such as the green regions is still insufficient. Strong internal electric field perpendicular to the heterointerfaces of the quantum wells is thought to be the major obstacle for achieving high-efficiency green or longer wavelength LEDs. The use of nonpolar a-plane nitrides is a potential solution for overcoming this problem. High-crystallinity a-GaN is essential for achieving high-performance LEDs. In this study, we report on the improvement of the quality of a-GaN on 0.5°-off r-plane substrates by the combination of the insertion of a thick AlGaN layer and lateral growth on a grooved a-GaN layer by high-growth-rate metallorganic vapor phase epitaxy (MOVPE). In addition, LEDs on a-GaN were fabricated. a-GaN was grown on 0.5°-off r-plane sapphire substrates.[1] After thermal cleaning of the r-plane sapphire substrate in hyrogen atmosphere at a temperature of 1150°C, it was cooled to 1100°C, at which grow an a-AlN layer about 200 nm thick followed by a 700 nm thick a-AlGaN layer and undoped a-GaN layer about 2.0

μm thick were grown. Insertion of a-AlGaN is found to be effective in reducing defects in a-GaN. The grooves along the <10-10> direction were fabricated by conventional photolithography and reactive ion etching techniques. The width, spacing and depth of the groove were 18 μm, 3 μm and 2.5μm, respectively. Subsequently, 30-μm-thick a-GaN was grown at a high-growth-rate ($\sim$55 μ m/h) by MOVPE. Plan-view TEM showed a distinct reduction in the threading dislocation density and stacking fault density on the groove region compared with the layers grown on the terrace region. AFM showed an RMS surface roughness as low as 0.26 nm on the groove. LEDs with a-GaInN as the active layer were grown on an r-plane sapphire substrate with grooved a-GaN. LEDs having the same structure were also fabricated on planar a-GaN for comparison. The output power of the LED on the grooved a-GaN was about fifty times higher than that of the LED fabricated on planar a-GaN. [1] A. Honshio, Y. Miyake, H. Kasugai, T. Kawashima, K. Iida, M. Tsuda, M. Iwaya, S. Kamiyama, H. Amano, and I. Akasaki: Ext. Abstr. (65th Autumn Meet 2004); Japan Society of Applied Physics and Related Societies, 2a-W-2.

4:30 PM FF7.8/EE5.8

Characterization of a-plane AlGaN/GaN heterostructure grown on r-plane sapphire substrate. Motoaki Iwaya, Yoshizane Okadome, Yousuke Tsuchiya, Hiroko Furukawa, Akira Honshio, Yasuto Miyake, Satoshi Kamiyama, Hiroshi Amano and Isamu Akasaki; Faculty of Science and Technology, 21st Century COE Program "Nano-Factory", Meijo University, Nagoya, Japan.

Although high-efficiency nitride-based light-emitting devices in the visible short-wavelength range have been achieved using strained GaInN quantum wells (QWs), they still have several problems such as a strong internal electric field caused by piezoelectricity. Most of these QWs are grown on c-plane GaN, thus large piezoelectric field in the QWs is induced. Nonpolar a-plane nitrides potentially solve these problems. In order to grow well-designed device structures using a-plane nitrides, it is essential to characterize the strain in the ternary alloy layers. The strain in the a-plane nitride heterostructure is quite complicated compared with the biaxial strain in the c-plane nitride heterostructures. In this study, the strain in an a-plane AlGaN (a-AlGaN) on a-plane GaN (a-GaN) was characterized by X-ray diffraction (XRD). Unisotropic strain and the composition of alloys in the strained ternary alloy layer of a-AlGaN on a-GaN was precisely determined using the high-resolution X-ray diffraction profile. The a-plane AlGaN/GaN heterostructure was epitaxially grown on r-plane sapphire by metalorganic vapor phase epitaxy. The a-AlGaN layer was approximately 50 nm thick grown on 4μm thick a-GaN. As the strain is uniaxial in the a-plane nitride heterostruxture, the XRD reciprocal lattice space mappings had to be performed using two planes to characterize the strain in the a-plane AlGaN/GaN heterostructure. In order to determine the composition of the strained a-AlGaN grown on the a-GaN, we measured XRD 2θ-ω scan profiles of (11-20) and (0002), and then calculated the alloy composition using the elastic stiffness constants. The XRD reciprocal lattice space mapping (RSM) was carried out around (11-22) and (20-20), where the (11-22) diffraction revealed the strain along the C-axis and the (20-20) diffraction revealed the strain along the M-axis. In the RSM around (11-22) diffraction, it was found that the diffraction spot of AlGaN was not located exactly above that of GaN, which means that the lattice constant c of the AlGaN was slightly different from that of GaN. Therefore, AlGaN was relaxed partially along the C-axis. On the other hand, the (20-20) diffraction showed that the in-plane lattice constant of AlGaN perfectly matched with that of GaN, which shows that AlGaN was grown coherently on the GaN along the M-axis. At the surface of the sample, a small number of cracks were observed only along the M-axis. The slight relaxation of the AlGaN only in one direction must be due to the tensile stress generated during the growth along the C-axis, which is larger than that along the M-axis. Dependence of the AlN molar fraction and strain relaxation will be discussed. Acknowledgements: The authors would like to thank Mr. M. Tsuda, Kyocera Corp. for preparing r-plane sapphire substrate.

4:45 PM FF7.9/EE5.9

Optimization of (10-1-1) Semipolar InGaN/GaN Multiple Quantum Wells for the Growth of Semipolar Light Emitting Diodes. Arpan Chakraborty, Troy Baker, Feng Wu, Jason Winders, Stacia Keller, Steven P. DenBaars, James S. Speck, Shuji Nakamura and Umesh K. Mishra; UCSB, Santa Barbara, California.

We investigated the growth, structural and luminescence properties of semipolar (10-1-1) InGaN/GaN multiple-quantum wells (MQWs) and optimized the MQW parameters for the growth of semipolar light-emitting diodes (LEDs). Conventional c-plane III-nitrides-based LEDs and laser diodes are characterized by the presence of polarization discontinuities at the heterointerfaces of the QWs. This gives rise to electric field and causes band bending, which results in the quantum confined stark effect in the QWs. The consequences of this effect are decreased recombination efficiency, red-shifted emission, and blue shifting of the emission with increasing drive current. Semipolar planes extend diagonally across the hexagonal unit cell and form an angle with the c-plane other than 90° and the polarization vector is tilted with respect to the growth direction. This results in reduced polarization effects. Also, for specific strain states on specific semipolar planes, there will be zero net polarization in the growth direction. Therefore, optoelectronic devices grown and fabricated along semipolar direction promises to be an effective means of improving their performance over conventional devices. Recently, we have grown semipolar (10-1-1) and (10-1-3) oriented GaN films on spinel and sapphire substrate. We found semipolar growth to be stable under a wide range of growth conditions. However, in comparison to c-plane InGaN/GaN MQWs, very little is known about the properties of semipolar quantum wells. 12 periods InGaN/GaN MQW samples were grown by metal organic chemical vapor deposition (MOCVD) on concurrently loaded hydride vapor-phase epitaxy grown (10-1-1) GaN templates grown on spinel substrate, and planar c-GaN templates. Effects of growth conditions, viz. temperature and reactor pressure, on the composition and the photoluminescence properties were investigated. The properties of the semipolar (10-1-1) InGaN/GaN MQWs were compared to those of c-plane. High resolution X-Ray analysis revealed that the incorporation efficiency of indium in the semipolar (10-1-1) InGaN/GaN MQWs was comparable to the c-plane QWs. The brightness and the full width at half-maximum of the emission from the semipolar QWs improved significantly when the QWs were grown in the pressure range of 400-500 Torr. The surface, analyzed by AFM, consisted of parallel ridges oriented perpendicular to the GaN (10-1-2) direction. Cross-sectional transmission electron microscopy was used to image the MQW microstructure. An optimum well width of 4 nm and a barrier width of 14 nm were determined. LEDs were fabricated on (10-1-1) GaN templates using the optimized MQW parameters had an on-wafer output power as high as 0.63 mW at 300 mA drive current. The LEDs had an electroluminescence peak at 439 nm with no shift with the increase in drive current, suggesting the absence of electric field in the quantum wells. This is the first demonstration of light-emitting diodes grown on semipolar GaN templates.

SESSION FF8: Poster Session: InN
Chairs: Juergen Christen and Tsvetanka Jeleva
Tuesday Evening, November 29, 2005
8:00 PM
Exhibition Hall D (Hynes)

FF8.1

Growth of InGaN Alloys with High Indium Concentration by Plasma-assisted MBE. Josh Abell[1], Papo Chen[1], Theodore Moustakas[1], Lin Zhou[2] and David Smith[2]; [1]Boston University, Boston, Massachusetts; [2]Arizona State University, Tempe, Arizona.

The recent discovery that InN is a narrow gap semiconductor (Eg = 0.7 eV) broadens the spectrum of potential applications of III-nitride semiconductors. One challenge is to develop methods of growing InGaN and InAlN alloys with high InN mol fraction without problems associated with phase separation. In the early literature, the phase separation in InGaN alloys was attributed either to spinodal decomposition [1, 2] or to "composition pulling effect" associated with the nature of the template on which the InGaN alloys were grown [3]. If the second interpretation is correct, then investigation of the nature of templates for the growth of InGaN alloys becomes very important to suppress phase separation. In this paper, we investigated and compared various nucleation steps for the growth of InGaN alloys in the entire alloy composition on (0001) sapphire by RF plasma-assisted molecular beam epitaxy. Such nucleation steps include InN quantum dots, low temperature InN buffers, a combination of these two steps and InGaN buffers of identical composition as the final film. The films are characterized in-situ by reflection high energy electron diffraction (RHEED) and by monitoring the evolution of stress during film growth. Furthermore, the films were also characterized ex-situ by atomic force microscopy (AFM), four circle x-ray diffractometry, transmission electron microscopy (TEM), optical transmission, photoluminescence and Hall effect measurements. So far, we have grown and investigated films with high InN mole fraction (70-100%). Our studies indicate that the growth of high quality InGaN films on (0001) sapphire substrates requires the conversion of the surface of the sapphire substrate from Al_2O_3 to AlN by exposing the substrate to a nitrogen-plasma at a certain temperature and for a certain period of time (nitridation). InGaN films grown using only InN quantum dots (QDs) were polycrystalline. Films grown on low temperature InN buffer (Ts = 280°C) were single crystals but with relatively wide (0002) rocking curves. InGaN films formed by combining these two nucleation steps had the best crystalline quality, with on axis rocking curve of 19 arcmin, while those grown on the low temperature buffer had significantly higher on axis rocking curves (80 arcmin). Phase separation has only been observed in films grown on thick InN templates but not on samples grown directly on thin InN buffers.

These studies and their correlation with optoelectronic properties of the films will be discussed. References 1: I. Ho and G. B. Stringfellow, Appl. Phys. Lett. 69, 2701 (1996). 2: R. Singh, D. Doppalapudi, T. D. Moustakas and L. T. Romano, Appl. Phys. Lett. 70, 1089 (1997). 3: Y. Kawaguchi et al, Mat. Res. Soc. Symp. Proc. Vol. 449, 89 (1997).

FF8.2
InN Nano Rodes and Epitaxial Layers Grown by HVPE.
Alexander Syrkin[1], Alexander Usikov[1], Oleg Kovalenkov[1], Vladimir Ivantsov[1], Vitali Soukhoveev[1], Vladimir Dmitriev[1], Charles Collins[2] and Eric Readinger[3]; [1]Technologies and Devices International, Inc., Silver Spring, Maryland; [2]U.S. Army Research Laboratory, Adelphi, Maryland; [3]Electrical And Computer Engineering, University of Maryland, College Park, Maryland.

Group III nitride compounds comprising MQW InGaN-based active regions have attracted much attention as device structures for short wavelength emitters operated in visible and ultra-violet spectral range. Hydride vapor phase epitaxy (HVPE) is well-known method capable of producing thick low-defect layers of GaN, AlGaN, and AlN, as well as free-standing GaN and AlN wafers. However, results on HVPE growth of InN and InGaN materials are limited. One of the major technical issues in the development of InN material is low dissociation temperature and high dissociation pressure of InN. In this paper we report on novel results on HVPE growth of InN and InGaN materials. The growth processes were carried out at atmospheric pressure in a hot wall quarts tube reactor with a resistively heated furnace. Growth temperature was varied from 500oC to 700oC. Ammonia (NH3) and hydrogen chloride (HCl) were used as active gases and argon served as a carrier gas. For InN and InGaN growth, HCl gas was passed over In and Ga sources, containing metallic indium and gallium, respectively. V/III ratio in the vapor phase was varied from 3 to 60. The growth was performed on sapphire substrates and on GaN, AlGaN, and AlN templates. X-ray diffraction studis confirmed formation of InN materials. Depending on growth conditions, formation of continuous layers or nano-rods was observed. InN nano-rods were grown on sapphire substrates forming hexagon prisms of about 400-600 nm in length and 60-80 nm in cross section. Material characterization results obtained by electron microscopy, x-ray diffraction, photoluminescence, and atomic force microscopy will be presented. HVPE growth of InN and InGaN materials opens novel perspectives for substrate and device applications of group III nitride semiconductors.

FF8.3
The Relationship between InN Properties and Hydrogen and Nitrogen. Maria Losurdo[1,2], Giovanni Bruno[1], Tong-Ho Kim[2], Pae Wu[2], Soojeong Choi[2], Mike Morse[2], April Brown[2], Francesco Masia[3], Antonio Polimeni[3] and Maria M Giangregorio[1]; [1]Chemistry, IMIP-CNR, Bari, Italy; [2]electrical and Computer Engineering, Duke University, Durham, North Carolina; [3]Physics, Universita La Sapienza, Rome, Italy.

The bandgap of InN has long been thought to be approximately 1.9 eV. Recently, various values of the optical band gap from 0.7 eV to 1.7 eV have been correlated with the measured free electron concentration. While progress has been made, the discrepancy in the data in the literature indicates that the fundamental optical properties of InN, including the actual band gap value and higher-energy interband transitions, and their dependence on defects is not fully understood. One of the primary issues primarily under investigation is the impact of carrier concentration, doping and defects on the bandgap and optical properties of InN. In this context, there is particular interest in investigating the effect of hydrogen and nitrogen on InN, since both hydrogen and nitrogen vacancies can contribute to the residual n-type carrier concentration of InN. The present work presents a study of InN structural, morphological, optical and electronic property modification upon interaction with atomic hydrogen and nitrogen produced by remote plasmas of H2 and N2, respectively. InN films with thicknesses ranging from 270 to 885 nm were grown by r.f. plasma assisted MBE on 6H-SiC substrates using a two-step process consisting of deposition of a thin low-temperature InN layer followed by annealing and the deposition of the epitaxial layer at 450C and V/III ratio. Post-growth exposure to atomic hydrogen and nitrogen by remote plasma sources was carried out at room temperature under various doses. In situ real time monitoring of the InN growth process and subsequent interaction with atomic hydrogen and nitrogen was carried out using spectroscopic ellipsometry. Spectroscopic ellipsometric (SE) spectra of the dielectric function acquired from 0.75 to 6.5 eV have been used for investigating the impact of the hydrogen incorporation and nitrogen vacancies on the optical gap and higher band-to-band transitions as a function of film structure and post-growth treatments. We also present data on X-ray diffraction to relate the effect of growth condition on the film structure, on atomic force microscopy (AFM) for the modification of the InN surface morphology by the interaction with hydrogen and nitrogen, on the electrical properties, which have been studied using the Van-der-Paw Hall measurement and electrical force microscopy, for variation of the electron carrier concentration and mobility due to hydrogen and nitrogen, and, finally, on the optical properties as assessed by photoluminescence and ellipsometry. We find that nitrogen vacancies contribute to the high residual electron concentration and decrease electron mobility. Saturation of nitrogen vacancies can decrease the carrier concentration and increase mobility. However, nitrogen interacts with InN inducing morphological modifications and degrading optical properties.

FF8.4
Epitaxial growth of InN on nearly lattice matched (Mn,Zn)Fe_2O_4 by pulsed laser deposition. Kazuya Mitamura[1], Jitsuo Ohta[2,3], Hiroshi Fujioka[2,3] and Masaharu Oshima[1]; [1]Department of Applied Chemistry, The University of Tokyo, Tokyo, Japan; [2]Institute of Industrial Science, The University of Tokyo, Tokyo, Japan; [3]Kanagawa Academy of Science and Technology, Kanagawa, Japan.

It is well known that the large lattice mismatch between InN films and sapphire, which is the most commonly used substrate, causes a high density of structural defects in the InN films. To solve this problem, the use of nearly-lattice-matched substrates has been highly requested. (Mn,Zn)Fe_2O_4 is a promising candidate for a substrate of InN heteroepitaxial growth because of its small lattice mismatch of 2.0% with InN. However, growth of InN with conventional growth techniques such as MBE leads to formation of thick interfacial layers because (Mn,Zn)Fe_2O_4 reacts easily with InN at high temperatures. Recently, we have reported that the growth temperature of group III nitrides can be reduced even to room temperature (RT) by the use of pulsed laser deposition (PLD)[1] and that the interfacial reaction is suppressed by the low temperature growth. In this presentation, we will discuss the use of RT InN films as a buffer layer for the epitaxial growth of InN on (Mn,Zn)Fe_2O_4 substrates. InN films were grown on (Mn,Zn)Fe_2O_4 (111) substrates by an RF-plasma assisted UHV-PLD apparatus with a background pressure of 5.0×10^{-10} Torr. The growth temperature was varied from RT to 550°C. KrF excimer laser pulses (λ=248nm, τ=20ns) ablated an In metal (99.9999%) target with an energy density of approximately 3 J/cm^2. The characterization of the heterointerface and the structural properties of InN films were performed by RHEED, HRXRD, GIXR, and AFM. The RHEED pattern for the RT-grown InN film showed clear streaks, which indicate the successful epitaxial growth of high quality InN, while that for the InN film grown at 550 °C contains both spots and rings indicating the degradation of crystalline quality. AFM observations have revealed that the surface of the RT-grown InN film was quite smooth with the stepped structure and the root mean square (rms) values was approximately 0.4 nm. On the other hand, the surface of InN films grown at 550 °C was quite rough and the rms value was 41 nm. These results indicate that the crystalline quality and the surface flatness of InN films are improved by the reduction in the growth temperature, which can be attributed to the suppression of the interfacial reactions between InN and (Mn,Zn)Fe_2O_4. GIXR measurements have revealed that the thickness of the interfacial layer is, in fact, reduced from 15 nm to 8.4 nm with the decrease of the growth temperature from 550 °C to RT. Then, we grew InN at 550 °C on RT-grown InN to investigate the feasibility of the use of RT InN layers as buffer layers for growth of InN on (Mn,Zn)Fe_2O_4. Growth of high quality InN on the RT buffer layers with smooth surfaces even at 550 °C was confirmed by RHEED and AFM observations. These results indicate that the use of RT InN epitaxial buffer layer leads to suppression of the interfacial reactions and improvement in the InN crystalline quality. Reference: [1]. J. Ohta et al., Appl. Phys. Lett. 83, 3060 (2003).

FF8.5
Structure of InN films grown on single crystalline ZnO substrates prepared by molecular beam epitaxy.
Takeshi Ohgaki[1], Tsuyoshi Ohnishi[2], Naoki Ohashi[3], Isao Sakaguchi[3], Mikk Lippmaa[2], Hajime Haneda[3] and Atsuo Yasumori[1]; [1]Department of Materials Science and Technology, Tokyo University of Science, Chiba, Japan; [2]Institute for Solid State Physics, The University of Tokyo, Chiba, Japan; [3]Advanced Materials Laboratory, National Institute for Materials Science, Ibaraki, Japan.

Zinc oxide (ZnO) is a possible material for lattice-matched substrate for hetero-epitaxial growth of III-V nitride semiconductors. In this study, we investigated growth condition dependence on polarity and crystallinity of indium nitride (InN) films grown on single crystalline c(+)-ZnO and c(-)-ZnO substrate. The samples were prepared with molecular beam epitaxy using an r. f. plasma cell for the nitrogen source. The film growth was initiated by simultaneously exposing the ZnO surface to incident In and N fluxes; namely, neither nitridation nor metallization of the substrate surface were done. The films were grown continuously at a certain substrate temperature, and any sort of buffer layer was not formed at the InN/ZnO interfaces. The structure and crystallinity of the obtained films were characterized with x-ray diffraction (XRD) and transmission electron microscopy

(TEM). Polarity of the films were determined by coaxial impact-collision ion scattering spectroscopy (CAICISS). The cross-sectional TEM observation revealed that structure of the InN films varied with the polarity of ZnO substrate. In fact, InN films grown on c(+)-ZnO had columnar structure with grain size of about 100 nm, while those grown on c(-)-ZnO were single crystalline films with the threading dislocation parallel to the growth direction. Corresponding to the difference in micro-structures, crystal-quality of InN films also depended on the polarity of ZnO substrate. The FWHM of the x-ray rocking curve for 0002 diffraction for the InN films grown on c(-)-ZnO was about 150 arcsec, which compared with 1000 arcsec or more for the InN films grown on c(+)-ZnO substrate. This high crystallinity of InN films on c(-)-ZnO can be explained by assuming that the low-crystalline InN layer deposited during the initial stage of crystal growth acted as a self-buffer layer. In fact, the XRD w-rocking curves of the InN (0002) diffraction peak of 20-nm-thick films had both broad and sharp peaks, while those of 150-nm-thick films had mainly sharp peaks. It is therefore reasonable to assume that a low-crystalline InN layer caused by the large lattice mismatch formed spontaneously during the initial growth stage and then high-crystalline InN films grew on this layer. The polarity and interfacial structure of InN films on ZnO single crystals will be also discussed.

FF8.6

Temperature Dependence of Mobility and Carrier Density in InN Films. J. Thakur[1], Vaman M. Naik[2], R. Naik[3], D. Haddad[3], G. Auner[1], H. Lu[4] and W. Schaff[4]; [1]Department of Electrical and Computer Engineering, Wayne State University, Detroit, Michigan; [2]Department of Natural Sciences, U Michigan-Dearborn, Dearborn, Michigan; [3]Department of Physics and Astronomy, Wayne State University, Detroit, Michigan; [4]Department of Electrical and Computer Engineering, Cornell University, Ithaca, New York.

We have investigated temperature dependence of Hall mobility and carrier density (n_e) for thin InN films with low ($n_e \sim 5\times10^{17}$ cm^{-3}) and high ($n_e \sim 3\times10^{20}$ cm^{-3}) carrier density grown by Molecular Beam Epitaxy (MBE) and Plasma Source Molecular Beam Epitaxy (PSMBE). In both the low and high carrier density films, a large concentration of carriers is observed at very low temperatures and carrier concentration remains almost independent of temperature, T, up to 300 K. The characteristics behavior of mobility for the low carrier density film is different from that of the high carrier density film particularly for T < 300 K. The low carrier density film shows a peak in the mobility at a temperature around 250 K in contrast to temperature independent mobility observed for the high carrier density film for T < 300K. Using Born-scattering theory, we have investigated various scattering mechanisms which contribute to the mobility of the films.

FF8.7

Abstract Withdrawn

FF8.8

Abstract Withdrawn

FF8.9

Electrical and optical properties of InN films grown on Si<111> substrate. Tatiana Komissarova[1], Nikolai Matrosov[1], Ludmila Ryabova[1], Dmitry Khokhlov[1], Josh Mangum[2], Taewoong Kim[2], Olga Kryliouk[2], Tim Anderson[2], Timur Burbaev[3] and Aleksander Belogorokhov[4]; [1]Physics Department, Moscow State University, Moscow, Russian Federation; [2]Department of Chemical Engineering, University of Florida, Gainesville, Florida; [3]Lebedev Physical Institute, Moscow, Russian Federation; [4]Institute of Rare Metals, Moscow, Russian Federation.

We have investigated transport and optical properties of the InN films grown by MOVPE on Si <111> substrate. Low pressure horizontal cold wall Nippon Sanso reactor was employed in this study. Trimethylindium, triethylgalium and ammonia were used as precursors in a nitrogen carrier gas. Both low temperatre (LT) InN and GaN buffer layers were studied. The specific growth conditions were as follows: reactor pressure P=100 Torr, V/III ratio varied from 6000 to 50000, LT InN buffer layer growth temperature T=450°C, LT GaN growth temperature T=560°C, InN main layer growth temperature T=530-560°C. Thickness of the films varied from 0.1 μm to 1.2 μm. Resistivity, Hall effect data and PL spectra were taken at temperatures 4.2-300 K, transmission and reflection spectra were measured at the room temperature. Concentration of free carriers in the films varied from $1.5\cdot10^{18}$ to $5\cdot10^{20}$ cm^{-3}, and the Hall mobility varied from 10 to 200 cm^2/V·s at the room temperature. Most of the InN films grown on sapphire substrate showed very weak temperature dependence of electrical properties. The use of Si<111> substrate and the GaN buffer layer, however, produces a significant change in the electrical properties. For these samples, the Hall coefficient showed a dramatic increase at lowering temperature, accompanied by a rise in the Hall mobility from 700 cm^2/V·s at T = 300 K to 9000 cm^2/V·s at T = 40 K. Further cooling has led to sharp decrease of the Hall coefficient and the Hall mobility. The results are interpreted in terms of presence of two types of carriers in InN. The mobile carriers most likely correspond to the transport via the conduction band, and the less mobile carriers provide transport via an impurity band or a surface state band that pins the Fermi level. In most of the samples the PL spectra form a wide band from 700 to 1200 meV. The maxima of the spectra lie in the range (700-1000) meV. For are the samples grown on Si<111> with a LT-GaN buffer, the PL spectra form a narrow line with a maximum at 1100 meV. Possible mechanisms of the carrier transport, formation of the PL, transmission and reflection spectra are discussed.

FF8.10

InN Growth by MOVPE at Low V-III Ratio in Chlorinating Environment. Sang Won Kang[1], Hwasoup Oh[1], Kyu Han Lee[1], Keunman Song[1], Dong-Yul Lee[1], Sunwoon Kim[1], Sangsu Hong[1], Hyun Jong Park[2], Olga Kryliouk[2] and Tim Anderson[2]; [1]Samsung Electro-Mechanics Co., LTD., Suwon, South Korea; [2]Chemical Engineering, University of Florida, Gainesville, Florida.

Growth of indium nitride (InN) using Metal Organic Vapor Phase Epitaxy (MOVPE) has several challenges. The growth temperature is limited to the range of 450~600°C because of the high vapor pressure of nitrogen over InN. The dissociation rate of NH_3 at this temperature range is very low. A high V/III (NH_3/TMIn) ratio (>10^4) is usually required to prevent indium metal droplet formation. A novel method was proposed to prevent co-deposition of indium metal. Indium metal droplet formation could be prevented at low V/III ratio (~2500) in chlorinating environment. The InN film was grown on GaN/sapphire substrate in N_2/HCl environment in a hot wall MOVPE reactor. Trimethylindium (TMIn) and NH_3were used as precursors in nitrogen atmosphere. The growth conditions for the InN growth were as follows: pressure=760 Torr; growth temperature = 550°C; V/III ratio=2500; carrier gas flow rate = N_2 4 slm. 10% HCl (with 90% N_2) flow was introduced together with carrier gas and precursors. HCl/TMIn inlet mole ratio was varied from 0 to 5. X-ray diffraction patterns were acquired for each sample to estimate the crystallinity and to determine the existence of indium metal droplets. Scanning Electron Microscopy (SEM) and Energy-Dispersive X-ray Spectroscopy (EDS) were used to investigate surface morphology and film composition of the grown and annealed samples. Auger Electron Spectroscopy (AES) was used to investigate possible chlorine contamination. A thermodynamic analysis of the In-N-Cl-H reaction system shows that indium metal can be selectively etched and the temperature range for selective indium metal etching is within the range for growth of InN. Based on both the thermodynamic analysis and experimental results, it is found that indium free InN can be grown at V/III ratio as low as 2500 by adding HCl in the HCl/TMI ratio range 0.3 to 1.4. Small amount of HCl flow (HCl/III ratio=0.3) could etch indium metal selectively at 550°C. Selective etching was verified by post growth annealing. Thereafter, InN was grown at low V/III ratio (2500) with HCl flow. Indium free InN was grown successfully in chlorinating environment. AES spectra show that there is no chlorine present in the film though it is grown in chlorinating environment. It was clearly shown that the indium formation at low V/III ratio is prevented as a benefit of HCl flow during MOVPE growth.

SESSION FF9: Poster Session: UV LED
Chairs: Juergen Christen and Tsvetanka Jeleva
Tuesday Evening, November 29, 2005
8:00 PM
Exhibition Hall D (Hynes)

FF9.1

Reliability and degradation modes of 280 nm deep UV LEDs on sapphire. Zheng Gong, Sameer Chhajed, Mikhail Erikovich Gaevski, Wenhong Sun, Vinod Advivarahan, Maxim Shatalov and Asif Khan; Electrical Engineering, University of South Carolina, Columbia, South Carolina.

Recently we have reported on 280 nm deep UV light emitting diodes with powers as high as 1 mW at 20 mA and wall plug efficiency as high as 1%. To avoid current crowding primarily due to the high Al-composition of the AlxGa1-xN buffer layers the LED mesa size was kept at 100 μm x 100 μm. This for a device current of 20 mA translates to a pump current density of 200 A/cm^2. In past we have also reported these high pump current densities to limit the device lifetime for 50 % power reduction to be only a few hundred hours. In this paper, we for the first time report a study of the degradation of AlGaN-based 280 nm LEDs that were grown on sapphire substrates using migration-enhanced metalorganic chemical vapor deposition process (MEMOCVD). Electroluminescence (EL), atomic force microscopy (AFM), cathodoluminescence (CL), and scanning electron

microscopy (SEM) observations showed that the degradation of deep UV LEDs generally fell into two categories: catastrophic degradation and gradual degradation. The catastrophic degradation was found to be mostly caused by the non-uniformity of surface morphology. AFM scan of the 100 μm x 100 μm emission area showed step-like morphology with average feature size of about 20 μm, depth of 20 nm and RMS surface roughness of 7.34 nm. We believe that alloying occurs between the electrode metals and the semiconductor at these step-like interfaces. The propagation of alloyed region damages the active layer leading to local shorting of the p-n junction leading to a catastrophic degradation of the device output powers and current voltage (I-V) characteristics. From temperature and bias dependent LED power degradation measurements it was found that the gradual power reduction had two characteristic time constants indicating two possible degradation mechanisms. The faster time constant was bias dependent and virtually constant with temperature whereas the second time constant (slower) varied exponentially with junction temperature. For this temperature dependent part, the activation energies of degradation were determined to be 0.21 eV and 0.24 eV under injected current density of 100 A/cm^2 and 200 A/cm^2 respectively. In this paper we will present the details of these measurements and use the experimental results to determine the possible degradation mechanisms.

FF9.2

Effect of Carrier-blocking Layers on the Emission Characteristics of AlGaN-based Ultraviolet Light Emitting Diodes and the Origins of their Parasitic Emissions.

Ji-Soo Park[1], Daryl W Fothergill[2], Xiyao Zhang[2], Seann M Bishop[1], John F Muth[2] and Robert F Davis[1]; [1]Department of Materials Science and Engineering, North Carolina State University, Raleigh, North Carolina; [2]Department of Electrical and Computer Engineering, North Carolina State University, Raleigh, North Carolina.

AlGaN-based thin film heterostructures suitable for ultraviolet light emitting diodes (UV LEDs) have been grown on 6H-SiC(0001) substrates and fabricated into working devices with and without p-type and n-type AlGaN carrier-blocking layers at the top and the bottom of the quantum wells, respectively, and with different p-GaN capping layer thickness. The principal emission from each device occurred at 353nm. The highest intensities of this peak were measured at all values of the injection current in the device with a p-type carrier-blocking layer at the top of the quantum well; this device also exhibited the highest values of light output power. Growth of an n-type carrier-blocking layer at the bottom of the quantum wells had an adverse effect on the light emitting diode characteristics. Diodes without a p-type carrier-blocking layer showed a parasitic shoulder peak at $\sim$370nm. A parasitic shoulder peak also appeared at 365nm in all devices having a relatively thick p-GaN capping layer; this peak broadened with an increase in the thickness of this layer. A peak centered at $\sim$540nm and similar in breadth and intensity saturation at high light intensity to that observed in GaN was present in the spectra acquired from all the LEDs. The results and conclusions derived from electroluminescence and output power measurements as a function of injection current will be presented and used to explain the effect of n-type and p-type carrier blocking layers on the emission characteristics of the UV LEDs. The origins of the parasitic emissions will also be discussed.

FF9.3

Efficient 350 nm-Band Quaternary InAlGaN UV-LEDs Fabricated on High-Quality AlN Buffer Layers.

Hideki Hirayama[1], Takayoshi Takano[2] and Yukihiro Kondo[1,2]; [1]Advanced Devices Laboratory, Riken, Saitama, Japan; [2]Matsushita Electric Works, Osaka, Japan.

For the realization of commercially available low-cost and high-power ultraviolet light-emitting diodes (UV-LEDs), the use of quaternary InAlGaN is very attractive, because high-efficiency UV emission can be obtained due to In-incorporation effects even it is deposited on high threading-dislocation density (TDD) buffer layers grown on sapphire substrates. The use of high-quality transparent AlN or AlGaN buffer layer is also very important for realizing a high extraction efficiency of UV light for the UV-LEDs. In this work, we fabricated 350-nm-band InAlGaN multi-quantum-well (MQW) UV-LEDs on high-quality AlN buffer layers, and obtained efficient UV emission under room temperature (RT) CW current injection. LED structures were grown by low-pressure (76 Torr) metalorganic vapor phase epitaxy (MOVPE) on (0001) sapphire substrates. The LED layer structure consists of AlN buffer layer directly grown on the substrate with high-growth-temperature (HT-AlN), n-AlGaN buffer layer, undoped InAlGaN buffer layer, undoped Inx1Aly1Ga1-x1-y1N/Inx2Aly2Ga1-x2-y2N 3-layer MQW active layer, p-Al0.28Ga0.72N electron blocking layer, p-Al0.18Ga0.82N layer and p-GaN capping layer. The growth temperature of HT-AlN layer was 1270 degree C. Typical values of the full-width at half maximum (FWHM) of the omega-scan profiles (0002) of the X-ray diffraction (XRD) rocking curves measured for HT-AlN layer was as low as 45 arcsec. That for n-AlGaN buffer layer grown on the HT-AlN was less than 150 arcsec. Electroluminescence (EL) spectra of InAlGaN UV-LEDs on AlN buffer layers were measured under RT CW operation. Single peak emission was observed with the wavelength between 318-350 nm. The UV output power was measured from the back-side of the LED. The output power of the 350 nm LED was approximately 0.5mW at injection current of 40mA under RT CW operation. Maximum external quantum efficiency (EQE) was approximately 0.35%. The value of EQE is considered to be strongly depending on the electron overflow ratio into p-AlGaN layer. We consider that EQE values may be much improved by obtaining higher hole-concentration of the p-AlGaN layer and by using suitable barrier-height of electron-blocking layer.

FF9.4

Effect of edge dislocation defect reduction in GaN on silicon template on performance of overgrown violet light emitting diode. Fatemeh Shahedipour-Sandvik, Muhammad Jamil, James R. Grandusky, Vibhu Jindal and Eric Irissou; College of Nanoscale Science and Eng., University at Albany-SUNY, Albany, New York.

A new method has been developed (M. Jamil et al., accepted for publication in Appl. Phys. Lett. 2005) to overcome the two major obstacles in development of GaN-based devices on Si platform, mainly formation of crack density due to high thermal expansion coefficient mismatch and dislocation density in the range of 1010 cm-3 as a result of the 16% lattice mismatch between the epilayer and the substrate. Other methods have been successful in elimination of cracks or modest reduction of dislocation defects using techniques such as multi-buffer grown at low temperature and lateral epitaxial overgrowth, respectively. In our method we report an order of magnitude reduction of edge dislocation defects to 1x10$\hat{8}$ cm$\hat{-}$2, three times reduction in screw dislocation defects to 4x10$\hat{8}$ cm$\hat{-}$2, (as measured by cross sectional TEM) and great reduction in cracks during the same set of processing steps. In this report we demonstrate high quality violet (400nm) light emitting diode grown on the our newly developed complex AlN/Si substrate and present an investigation into the difference between characteristics of LEDs grown on this substrate and on as grown structures. This is to establish a relationship between role of edge dislocation defect and performance of violet LED. Previously it was shown that characteristics of LEDs with emission in the near UV were more affected by dislocation defects than those emitting in the blue but no distinction was made between the nature of extended defects responsible. In order to optimize performance of GaN-based devices a deeper understanding of the effect of extended defects on the characteristics of devices is needed. We show through extensive structural, optical and morphological studies that this substrate engineering scheme has a great potential in obtaining a compliant substrate for III-Nitride material system.

FF9.5

Optical Degradation of AlGaN and InGaN Light-emitting Diodes at Elevated Temperatures. Xian-An Cao, S. F. LeBoeuf and T. E. Stecher; GE Global Research, Niskayuna, New York.

The electroluminescence (EL) of AlGaN-based ultraviolet (UV) light-emitting diodes (LEDs) (265-365 nm) and InGaN-based visible LEDs (400-465 nm) was studied in the temperature range of 25-175 ^{o}C. The UV LEDs showed a much more rapid decrease in emission intensity with increasing junction temperature than the InGaN emitters. The temperature-dependence of the EL peak intensity can be described by $I = I_0 \exp(-T/T_1)$. The characteristic temperature T_1 decreased with increasing Al content in active region of the AlGaN LEDs (T_1 = 30-70 K) and decreasing In content in the InGaN LEDs (T_1 = 120-182 K). The high-energy and low-energy sides of the UV EL spectra had similar temperature dependence, indicating the dominant band-to-band transition in the AlGaN LEDs. In contrast, strong localization effects were retained in the InGaN LEDs up to 175 ^{o}C, leading to temperature-independent emission intensity at low-energy tails. These findings suggest that In segregation in InGaN-based emitters not only enhances the radiative efficiency at room temperature but also greatly improves their thermal stability, and illustrate the importance of increasing the cladding barriers in deep UV emitters for better carrier confinement. The AlGaN LEDs also exhibited much faster performance degradation over time under current stress at elevated temperatures. The correlation between optical decay and microstrutural changes in the UV LEDs under stress was established.

FF9.6

Growth and Process of Two-color Blue/Green Light-emitting Diodes with an n-i-p-i-n Configuration of Two Different Quantum-well Structures. Chi-Feng Huang, Tsung-Yi Tang, Dong-Ming Yeh, Chih-Feng Lu, Jian-Jang Huang and Chih-Chung Yang; Institute of Electro-Optical Eng., National Taiwan University, Taipei, Taiwan.

For implementing solid-state white-light source and color micro-display, various methods have been considered for mixing different colors. The most commonly used approach is the use of phosphors for transferring short-wavelength photons into long-wavelength ones. However, the use of phosphors leads to quite low conversion efficiency and the difficulty in packaging. In this research, we make efforts in fabricating single-chip all-semiconductor multiple-color light-emitting devices (LEDs). In other words, multiple-color emitting InGaN/GaN quantum wells (QWs) are to be grown. In growing such an epitaxial sample of two colors, two kinds of configuration can be used. The first one includes two diodes of the n-i-p-i-n structure. The second one consists of a single diode of two types of QW. In the first kind, the growth difficulties include the poor quality of QWs grown on the embedded Mg-doped p-type layer and the thermal effects of the high-temperature (1000 oC) growth of Mg-doped GaN on the underlying QWs. In growing a two-diode sample for blue and green light emissions, to overcome the difficulties, the blue single QW is grown first with an n-i-p structure. Then, two green-emitting QWs are grown on the top with a p-i-n structure. Also, All the Mg doping concentration, the p-type GaN thickness, and the p-type GaN growth temperature are minimized. The blue-emitting diode is grown first simply because its QW is not sensitive to the high temperature growth of the upper layers. Normally, such a thermal annealing process leads to the blue shift of luminescence spectrum or the degradation of crystal quality and hence photon-emission efficiency. Such effects are particularly significant in QWs of high indium contents. During the growth, for p-type activation of the embedded Mg-doped GaN, the growth is interrupted at 800 oC for 30 min with nitrogen flow right after the growth of the Mg-doped layer. The X-ray diffraction pattern clearly shows the combination of two QW structures of different indium compositions and QW widths. The photoluminescence measurement also shows two clear peaks around 450 and 510 nm. A basic electro-luminescence measurement indicates the feasibility of fabricating a blue/green two-color LED.

FF9.7

Analysis of high-power packages for white-light-emitting diode lamps with remote phosphor. Hong Luo[1], Jong Kyu Kim[2], Yangang Xi[1], E. Fred Schubert[1,2], Jaehee Cho[3], Cheolsoo Sone[3] and Yongjo Park[3]; [1]Department of Physics, Applied Physics and Astronomy, Rensselaer Polytechnic Institute, Troy, New York; [2]Electrical, Computer, and Systems Engineering Department, Rensselaer Polytechnic Institute, Troy, New York; [3]Photonics Program Team, Samsung Advanced Institute of Technology, Suwon, South Korea.

Phosphorescence efficiency in high-power white light-emitting diode (LED) lamps is investigated by three-dimensional ray tracing. The absorption of the phosphorescence by the LED chip is shown to be greatly reduced by employing a remote phosphor arrangement, which enhances the lamp efficiency. However, it is found that a significant fraction of the phosphorescence is trapped as whispering-gallery modes propagating along the circumference of the encapsulant. The abundance of whispering-gallery modes, which occur irrespective of the shape of the encapsulation dome, is shown to sensitively depend on the diffusivity of the reflector cup employed in the lamp. Dichromatic LED lamps with an optimized packaging configuration that employs a diffuse reflector cup and a remote phosphor were fabricated. The phosphorescence efficiency is found to be improved by 15.4% for blue-pumped yellow phosphor and 27% for ultraviolet-pumped blue phosphor. The experimental results are fully consistent with theoretical ray tracing simulations.

SESSION FF10: Poster Session: Electrical/Transport
Chairs: Juergen Christen and Tsvetanka Jeleva
Tuesday Evening, November 29, 2005
8:00 PM
Exhibition Hall D (Hynes)

FF10.1

Al mole fraction dependence of deep levels in AlGaN/GaN-HEMT structures estimated by CV profiling. Junjiroh Kikawa[1], Katsuhiro Imada[1], Tomoyuki Yamada[1], Tadayoshi Tsuchiya[1], Yuichi Hiroyama[1], Masayuki Iwami[1], Tsutomu Araki[2], Akira Suzuki[3,1] and Yasushi Nanishi[2]; [1]Advanced HF Devices R&D Center, R&A Association for Future Electron Devices, Kusatsu, Shiga, Japan; [2]Department of Photonics, Ritsumeikan Univercity, Kusatsu, Shiga, Japan; [3]Research Organization of Science and Engineering, Ritsumeikan Univercity, Kusatsu, Shiga, Japan.

GaN based high mobility electron transistors (HEMTs) have emerged as very attractive candidates for high-power applications. But the gate leak current of those devices is as much as two orders magnitude more than that in GaAs based HEMTs. The origin of this large leak current has been discussed by several institutes and universities, and deep levels play a major role in their models. To understand the behavior of gate leak current, we performed current-voltage (IV) measurements and capacitance-voltage (CV) measurements of AlGaN/GaN-HEMT structures and estimated energy depth of deep levels. The epitaxial layer structures employed in these studies were grown using metalorganic chemical vapor deposition, and consisted of a 30nm undoped AlxGa1-xN barrier layer and a 2μ m undoped GaN channel layer on a sapphire substrate. Al mole fractions of AlxGa1-xN barrier layer were from x=0.19 to x=0.35. Schottky junction structures were fabricated with Ni/Au as a gate metal and Ti/Al/Mo/Au as an ohmic contact. We performed IV measurements of those samples and observed the leak current has increased with an increase in Al mole fraction, as reported in the literatures. Then, by CV measurements we observed a distinct peak in CV profiling at low frequency in large leak current junctions. The integral of this peak was found to have a correlation with a leak current. The behavior of this peak might be described by the SRH model if we assume this peak is a phenomenon of an electron emission and capture by deep levels. Temperature and frequency dependences of this peak suggest this assumption. In this model, the amount of change of ionized deep levels by a small signal is expressed by the product of the amount of ionized deep levels and the partial differential of the distribution function of deep levels[1]. Because, the partial differential of the distribution function has a peak at Fermi level equal to the energy depth of deep levels, the amount of change of ionized deep levels has a peak at the same energy. Then Fermi level at the bias point where a peak appears in CV profiling corresponds to energy depth of deep levels. The Fermi level can be approximated by Fermi level of two dimension electron gas if Fermi level in a depletion layer is assumed to move in parallel with the conduction band of AlGaN. The Fermi level of two dimension electron gas can be calculated using the number of carriers obtained from the integral of CV profiling from zero to the peak bias point. The result of our samples was that the energy depth of deep levels is distributed from 320meV to 470meV for Al mole fraction from 0.19 to 0.30, respectively. This work was carried out under High-Power, High Frequency Gallium Nitride Device Project of NEDO. [1] T.Ohori et al.,J.Appl.Phys.,83,1223(1988)

FF10.2

Trapping behavior of deep defects in GaN layers and GaN based heterostructures investigated by Photo-Conductivity and Photo-Hall effect measurements. Hartmut Witte, Andre Krtschil, Armin Dadgar, Alois Krost and Juergen Christen; Institute of Experimental Physics, Otto-von-Guericke-University Magdeburg, Magdeburg, Germany.

GaN is a well-established material in devices such as blue laser diodes or transistor structures applied in high frequency and high temperature devices. In these layers and devices, the transport properties as well as the dynamic behavior are significantly influenced by all electronically active defects involving point or extended states. Therefore, we have investigated the trapping behavior of deep defects in conducting undoped, as well as in low Mg-doped and Fe-doped GaN layers on sapphire substrates and in AlGaN/GaN heterostructures on high purity Si- substrates grown by metal-organic vapor phase epitaxy. For the investigations we used spectral- dependent photo-induced conductivity and photo-Hall-effect measurements in the temperature region between 15 K and 400 K and at wavelengths between 240 nm and 900 nm (details see in /1/). On the basic of a critical analysis of the optical transitions and the trapping processes contributing to the photo-conductivity and to the photo-Hall effect we are able to distinguish between an electron or a hole trapping. This separation needs the simultaneous measurement of the photo-induced conductivity and the photo-Hall effect for a detailed analysis of the capture and emission behavior of the traps. In undoped GaN layers we found defect-to-band transitions between EG - (50 - 150) meV which show a strong electron capture or a hole emission which is similar to reference measurements in Mg- and Fe-doped samples. Furthermore, we correlated these measurements with results of thermally and optically admittance spectroscopy, deep level transient spectroscopy and surface scanning potential spectroscopy. Results are interpreted in terms of recharging of hole traps with activation energies up to 150 meV. These investigations were extended to complex heterostructures which give different results of the trapping behavior within the GaN layers depending on the quality of the heterostructure. Furthermore, in the near band region of the AlGaN layer we found indications of hole trapping. /1/ H.Witte et al : J. Appl. Phys. 97, 043710 (2005)

FF10.3

Resistivity Control of Unintentionally and Iron Doped GaN Films. Mariusz Rudzinski[1], V. Desmaris[2], P. R. Hageman[1], J. L. Weyher[1,3], T. Rodle[4], H. F. F. Jos[4], H. Zirath[2] and P. K. Larsen[1]; [1]Exp. Solid State Physics III, Institute for Molecules and Materials, Radboud University Nijmegen, Nijmegen, Netherlands; [2]Microwave Electronics Laboratory, Microtechnology and Nanoscience, Chalmers University of Technology, Gothenburg, Sweden; [3]High Pressure

Research Center of the Polish Academy of Sciences, Warsaw, Poland; [4]Philips Semiconductors, Nijmegen, Netherlands.

We report a comparative investigation of unintentional and iron doped GaN layers grown by metalorganic chemical vapor deposition (MOCVD) using sapphire and SiC as substrate. The different iron concentrations in the GaN films were determined by secondary ion mass spectrometry. The resistivity of the GaN layers was characterized by Hall effect measurements and by recording the leakage current between two isolated ohmic contacts at a constant distance from each other. When doping the first 0.3 μm of the film with Fe the resulting 2 μm thick GaN film grown on sapphire possessed a resistivity of 6x10^3 Ω*cm. In comparison, undoped GaN of the same thickness has a resistivity of 3 Ω*cm. X-ray diffraction rocking curves indicated a lower crystalline quality compared to the undoped films, showing that Fe doping increases the threading dislocation density which might be responsible for the increase in resistivity. In this manner the presence of Fe in the lattice works in the same way as changing the nucleation layer structure, which cause a change in the creation of different types of dislocations in the layer [1]. To investigate this option selective etching in a molten eutectic mixture of KOH-NaOH (E) with 10% of MgO powder (E+M) at 400°C [2] was used to reveal the type of defects, density, and its distribution over the wafer. However, no conclusive evidence is presented to exclude the deep acceptor nature of Fe being responsible for growth of semi-insulating GaN films. Considering the fact that unintentional GaN buffer is more required as a better solution for HEMT devices, further investigation is focused on unintentional GaN grown on SiC. It will be demonstrated that by changing the growth conditions and Al concentration of the nucleation layer the resistivity of the layer can be changed by a few orders of magnitude. Acknowledgements: The financial support of Philips Semiconductors B.V. Nijmegen is gratefully acknowledged. [1] A.P. Grzegorczyk, L. Macht, P.R. Hageman, J.L. Weyher, P.K. Larsen, J. Crystal Growth 273, 424 (2005). [2] G. Kamler, J.L. Weyher, I. Grzegory, J. Jezierska, T. Wosinski, J. Cryst. Growth 246, 21 (2002).

FF10.4

Deep level transient spectroscopy of InGaN/GaN multiple quantum well light emitting diodes. Jae Wook Kim[1], G. Hugh Song[1] and Jhang W. Lee[2]; [1]Dept. Info. & Comm., Gwangju Instituite of Science and Technology, Gwangju, South Korea; [2]Kowon Technology, Yongin, South Korea.

Comprehensive DLTS analysis of InGaN/GaN multiple quantum well (MQW) LEDs have not been reported yet, partly because of the complexity of the device structures and the difficulties in the interpretation of the DLTS signals. This paper presents our first successful DLTS analysis of the InGaN/GaN MQW active layers. In DLTS measurements of MQW LEDs we observed a unusual appearance of a minority carrier trap peak, beside the usual majority trap peaks, and the intensity of this peak increases as the pulse height increases at a fixed reverse bias. To interpret such results we proposed a model in which a highly asymmetric p+-n junction model consisting of unintentionally doped n-type MQW region and highly p-type doped AlGaN barrier. In this model we expect that a free hole tail can be extended to the n-type region adjacent to the junction boundary from the highly doped p-type layer and the occupation of hole traps in that n-type region can vary sensitively to reverse bias conditions. The simulation result made by Shockley-Read-Hall statistics is in good agreement with our experimental results. It concluded that the deep level defect are hole traps in the n-GaN barrier layers in the MQW active region and the activation energy is 0.7eV. We believe this is the first successful attempt to analyze the deep level trap in MQW active layer of GaN-based LED structures. This work has been supported in part by the KOSEF through the UFON-ERC Program, by the ITRC-CHOAN Program (Ministry of Information and Communications), by the BK 21 IT Project.

SESSION FF11: Poster Session: Nano
Chairs: Juergen Christen and Tsvetanka Jeleva
Tuesday Evening, November 29, 2005
8:00 PM
Exhibition Hall D (Hynes)

FF11.1

Epitaxal growth of InGaN quantum dots grown by MOVPE and RF-MBE and the structural and optical properties. Tomohiro Yamaguchi, Stephan Figge, Kathrin Sebald, Angelika Pretorius, Andreas Rosenauer, Juergen Gutowski and Detlef Hommel; Institute of Solid State Physics, University of Bremen, Bremen, Bremen, Germany.

$In_xGa_{1-x}N$ quantum dots (QDs) are attracting considerable attention to the realization of light emitting diodes (LEDs) and laser diodes (LDs) with the predicted improvement of device performance. Still there are many open fundamental questions how to realize QD structures. In this paper, we report on the epitaxy of $In_xGa_{1-x}N$ QDs grown by metal-organic vapor phase epitaxy (MOVPE) and radio-frequency molecular beam epitaxy (RF-MBE) and the structural and optical investigations by means of AFM, TEM and μ-PL. $In_xGa_{1-x}N$ QDs were grown on GaN template, prepared by MOVPE on sapphire (0001) substrate. The $In_xGa_{1-x}N$ dots were capped by a GaN layer or a low In-content $In_yGa_{1-y}N$ layer ($0<y<0.02$) with a thickness of 5 nm at the same temperature of $In_xGa_{1-x}N$ growth to prevent an evaporation of In from $In_xGa_{1-x}N$ dots. Then the structure was overgrown by a 30-nm thick GaN layer at a high temperature. $In_xGa_{1-x}N$ dots with a very high density over 5×10^{11} cm^{-2} and with an average height and diameter of 2 nm and 8-20 nm, respectively, were achieved by decreasing the growth temperature to 600°C and 450°C in MOVPE and MBE systems, respectively. Especially, in the case of samples grown by MOVPE, dots without misfit dislocations and with pronounced facets were observed. In regard to the optical properties using μ-PL, a broad $In_xGa_{1-x}N$ luminescence with sharp peaks was observed in the spectral regions between 2.8 and 2.9 eV. The sharp peak had a full width at half maximum of approximately 0.21 meV, which is in the order of the spectral resolution of the experimental setup. These narrow emission lines are attributed to strong localization centers. The dot-size homogeneity could be also controlled by decreasing the growth temperature. On the other hand, the PL intensity was getting weaker by decreasing the temperature. This might be due to an inferior crystalinity of the $In_xGa_{1-x}N$ dots and the GaN or $In_yGa_{1-y}N$ capping layer. The growth temperature is a critical parameter for the realization of $In_xGa_{1-x}N$ quantum dots. Furthermore we will discuss concept how to obtain homogeneous dots at high growth temperatures.

FF11.2

Determination of mean inner potential of gallium nitride nanowires using off-axis electron holography.
Andrew See Weng Wong[1], Ghim Wei Ho[2], Rafal B Dunin-Borkowski[1], Rachel A Oliver[1] and Colin J Humphreys[1]; [1]Materials Science and Metallurgy, University of Cambridge, Cambridge, Cambridge, United Kingdom; [2]Department of Electrical Engineering, Nanoscience Centre, University of Cambridge, Cambridge, Cambridge, United Kingdom.

Quantum wells in the InGaN/GaN system have attracted much attention because of their application to advanced wide-band-gap GaN-based optoelectronic devices such as light-emitting diodes and laser diodes. Control of the indium concentration in the InGaN layers in principle enables such devices to be operated at specific wavelengths over a wide range. Since wurtzite InGaN has large piezoelectric coefficients, an in-plane compressive stress in the InGaN layer due to lattice mismatch at a hetero-interface with GaN causes strong piezoelectric fields across the quantum well. Off-axis electron holography, which is an advanced transmission electron microscopy (TEM) technique can be employed to measure the electric field across the quantum well. The phase change of a high-energy electron passing through the specimen relative to vacuum is proportional to the electrostatic potential of the specimen and to its thickness. A major contribution to the measured electrostatic potential is the mean inner potential of the specimen Vo, which is the volume-averaged crystal potential. Vo typically takes values between 5V and 30V, depending on the composition and structure of the material. Its value is very sensitive to variations in charge density associated with bonding and ionicity in the crystal structure. Traditionally, experimental values of Vo in different materials have been obtained from wedge-shaped specimens obtained by cleaving. The advantage of obtaining wedge specimens from cleaving is that they are free from surface damage (which is not the case of ion-milled specimens). Coupled with a knowledge of the wedge angle, the specimen thickness can be determined accurately and correlated precisely with the observed phase change. However the measurements of experimental values of Vo for GaN suffer from the difficulty of cleaving wedges from GaN epitaxial layers that have been grown on sapphire or silcon carbide. In this study, we determine Vo from GaN nanowires that have been grown using chemical vapour deposition (CVD) with nickel as the catalyst. Typical growth temperatures and times are 950oC and 30 minutes respectively. The GaN nanowires were characterized using scanning electron microscopy, energy dispersive x-ray spectroscopy and conventional TEM. The nanowires are typically $<$ 20 nm in diameter although thicker wires have also been analysed. Experimental phase profiles have been compared with the simulated profiles. Analysis of several nanowires reveals that nanowire facetting (i.e. deviation from a circular cross-section) can introduce significant errors in the measurement of Vo, in addition to those from surface contamination and dynamical diffraction.

FF11.3

Raman scattering of self-assembled gallium nitride nanorods synthesized by plasma-assisted molecular beam epitaxy.
Dake Wang[1], Chin-Che Tin[1], John Williams[1], Minseo Park[1], Y. S.

Park[2], C. M. Park[2], T. W. Kang[2] and W.-C. Yang[2]; [1]Department of Physics, Auburn University, Auburn, Alabama; [2]Quantum Functional Semiconductor Research Center and Department of Physics, Dongguk University, Seoul, South Korea.

Gallium nitride (GaN) is an interesting material in the application of electronics and photonics. One-dimensional nanostructure of semiconducting material is considered as fundamental building blocks for nanoelectronic and nanophotonics. Aligned GaN nanorods were synthesized on Si using a plasma-assisted molecular beam epitaxy. Raman scattering experiment showed that the GaN nanorods are relatively strain-free. The electron concentration and electron mobility of the GaN nanorods were determined by the line shape analysis of the coupled A1(LO) phonon-plasmon mode. In the case of nanostructure, it is important to include thermal effect in determining the peak position of the uncoupled LO phonon mode. Therefore, we have considered the effect of laser heating on the shift of the Raman peak position. The local temperature of the nanorod was estimated based on the ratio of Stokes to anti-Stokes Raman peak intensity. We will present the general method of better determining the electronic parameters of the GaN nanostructures via Raman scattering.

FF11.4
Seeded Catalytic Growth of GaN Nanowires on Platinum Nanoparticles Obtained by Annealing Thin Pt Films. Jinyong Kim, Douglas Tham and John E. Fischer; Materials Science and Engineering, University of Pennsylvania, Philadelphia, Pennsylvania.

In a recent surprising result, we found that FIB-deposited nanoscale Pt catalyzes the growth of high quality GaN nanowires [1]. We have repeated the experiment, borrowing a technique well-known in carbon nanotube growth [2], namely depositing a thin PT film and annealing it to ball up the catalyst in a controlled manner. The motivation is to routinely obtain a narrow diameter distribution of small diameter GaN NW in which quantum confinement effects on electronic and vibronic properties should be manifest. Diameter uniformity will also be important for the development of applications. Our standard GaN growth method [1] is optimized for 900oC substrate temperature. Growth of GaN directly onto as-deposited Pt yields only large crystals, because 900oC is not high enough to ensure balling up of the Pt film. Conversely, GaN NWs can be grown after a separate heat-treatment of the Pt film. By separating the preparation of catalyst nanoparticles from NW growth, the NW size distribution can be controlled. We analyze the size distributions of both Pt catalyst and the resulting GaN NWs by AFM (Atomic Force Microscopy) and SEM (Scanning Electron Microscopy), and the atomic structure of GaN NWs is analyzed by TEM (Tunneling Electron Microscopy). This work is supported by the NSF NIRT Program under Grant No. DMR-0304178. 1. C. Y. Nam, J. Y. Kim, D. Tham, and J. E. Fischer, App. Phys. Lett. 86, 193112 (2005). 2. C. Bower, O. Zhou, W. Zhu, D. J. Werder, and S. Jin, App. Phys. Lett. 77, 2767 (2000).

FF11.5
Fast High-Density Low-Pressure Plasma Synthesis of GaN Nanocrystals. Uwe R. Kortshagen[1], Elijah Thimsen[1], Feng Liao[1], Joe Johnson[2] and Stephen A. Campbell[2]; [1]Mechanical Engineering, University of Minnesota, Minneapolis, Minnesota; [2]Electrical and Computer Engineering, University of Minnesota, Minneapolis, Minnesota.

Gallium nitride is studied based on its excellent optical properties and wide band gap for a variety of applications including high-brightness light emitting diodes and near UV lasers, and solar blind UV detectors. Aside from GaN thin films, GaN nanocrystals attract increasing attention, in part, due to their stipulated potential for enabling the growth of GaN single crystals. Among the synthesis routes for GaN nanocrystals studied so far are high temperature furnace reactions of Ga vapor with ammonia, furnace reactions of gallium trichloride with ammonia, thermal plasma arc induced reactions of metallic gallium with nitrogen/ammonia mixtures, metathesis (exchange) reactions between gallium chloride and sodium azide that produces gallium nitride nanoparticles, and liquid phase reaction of gallium chloride and lithium nitride in aromatic solvents mixed with capping agents (trioctylphosphine, TOPO). However, most of these reaction schemes have certain shortcomings. For instance, batch process type schemes usually require very long reaction times of many hours to days. Pure gas phase schemes suffer from the fact that nanocrystals are prone to agglomeration that increases the particle size in an often undesired fashion. Here we discuss a low-pressure nonthermal plasma based scheme that overcomes these problems in an elegant manner. Plasma synthesis strongly reduces or completely eliminates agglomeration since the particles in a plasma are unipolarly negatively charged. In addition, low pressure plasmas provide a unique non-equilibrium environment in which the particle temperature can exceed the temperature of the surrounding gas by several hundreds of Kelvin due to strongly exothermic processes at the particle surface; this enables achieving a high yield of crystalline material in a low temperature environment at a fast rate. In particular, nanocrystals created by our plasma approach are synthesized on timescale of a few milliseconds. GaN nanocrystals were synthesized in a low-pressure microwave plasma. A surfaguide wave launcher was used to generate a surface wave sustained plasma at 2.45 GHz at power levels of 250-450 W in a 1/4 inch inner diameter quartz tube. Gallium trichloride ($\sim$0.5 sccm) was used as a precursor in an argon carrier gas ($\sim$75 sccm) and reacted with ammonia (250-500 sccm). The total gas pressure was about $\sim$1 kPa. The plasma induces efficient dissociation of the precursor gases which leads to the formation of GaN nanocyrstals. The residence time of the nanocrystals in the plasma zone is of the order 3-5 ms. Transmission electron microscope studies of the particles confirm the presence of 20-50 nm GaN nanocrystals. X-ray diffraction also provides evidence of the synthesis of GaN nanopowder. The relation of plasma process parameters and nanocrystal properties are discussed. This work is supported in part by NSF under MRSEC Award Number DMR-0212302.

FF11.6
Synthesis, Structure and Properties of Novel III-V Semiconductor Single-Crystalline Nanotubes. Longwei Yin and Yoshio Bando; Advanced Materials Laboratory, National Institute for Mateials Science, Tsukuba, Ibaraki, Japan.

Novel III-V semiconductor single-crystalline nanotubes including InN, GaN, InP, have been synthesized via controllable self-assembling and template-inducing routes. The InN nanotubes and nanowires are grown via a controlled carbonitridation thermal chemical route, which could be explained according to different growth dynamics at different synthesis temperatures. The InN nanotube and nanowire growth are related to diffusion-limited and kinetically-limited process, respectively. The structure and optical properties of InN are studied. The AlN nanotubes are fabricated via a MWCNTs-template inducing route. The MWCNTs act as templates and reducing reactants to control the morphology and size of AlN nanotubes. The synthesized AlN nanotubes display good field emission property. The InP nanotubes are synthesized using previously formed In2O3 nanotubes as templates. The structural stability of InP nanotubes are studied under strong electron beam irradiation, and the optical properties of the InP nanotubes are characterized by photoluminescence and cathodluminescence spectra. It is believed that the synthesized III-V nanotubes could offer opportunities for further fundamental researches and could find potential applications for the growing demands from nanoscale science and technology of semiconductor. Ref. [1] L.W. Yin, Y. Bando, D.Golberg, M.S. Li, Adv.Mater. 2004,16, 1833. [2] L.W. Yin, Y. Bando, Y.C. Zhu, D.Golberg, M.S. Li, Adv.Mater. 2005,17, 213. [3] L.W. Yin, Y. Bando, Y.C. Zhu, D. Golberg, M.S. Li, Appl.Phys. Lett. 2004, 84, 3912. [4] L.W. Yin, Y. Bando, Y.C. Zhu, D. Golberg, M.S. Li, Appl. Phys. Lett. 2004, 85, 3869. [5] J. Goldberger, R. He, Y. Zhang, S. Lee, H. Yan, H.J.Choi, P. Yang, Nature 2003, 422, 599. [6] Q. Wu, Z. Hu, X. Wang, Y. Lu, X. Chen, H. Xu, Y. Chen, J.Am. Chem. Soc. 2003, 125,10176. [7] W. Han, Y. Bando, K. Kurashima, T. Sato, Appl. Phys. Lett. 1998, 23, 3085.

FF11.7
InAlN Nanostructures: Strain Morphology, and Optical Properties. Yuriy Volodymyr Danylyuk[1], Daniel G. Georgiev[1], Gregory W. Auner[1], Ratna Naik[2] and Vaman M. Naik[3]; [1]ECE SSIM, Wayne State University, Detroit, Michigan; [2]Physics, Wayne State University, Detroit, Michigan; [3]Department of Natural Sciences, University of Michigan-Dearborn, Dearborn, Michigan.

We present experimental work on InAlN nanostructures grown on an AlN buffer layer deposited on sapphire (0001) by Plasma Source Molecular Beam Epitaxy. InAlN dots of controlled size were fabricated by using specific growth conditions and taking advantage of self-organization growth. The films are epitaxial with no phase segregation as shown by x-ray diffraction scans. In-situ RHEED scan mode measurements were used to determine RHEED intensity oscillations, strain profiles, and coherence length profiles simultaneously and the results indicate a Stranski-Krastanov type growth mode. Nanostructures as small as 10 nm, were characterized by atomic force microscopy (AFM), micro-Raman, photoluminescence, and UV-VIS-IR spectroscopy. An in-plane residual strain field was deduced from the E2 phonon frequency shift in the Raman spectra and compared with RHEED pattern strain profiles. We also observe reproducible light-emission peaks at 2.16, and 2.23 eV for Al1-xInxN (x = 0.65) at 300 K. We attribute the peaks to electron confinement in the dots due to the strong electric field of piezoelectric and spontaneous polarization that is characteristic to nitride semiconductor compounds.

FF11.8
Opto-electronic Simulation of GaN Nanowire Lasers. Liang Chen and Elias Towe; Department of Electrical and Computer Engineering, Carnegie Mellon University, Pittsburgh, Pennsylvania.

Nanowires are one dimensional nanostructures that can be synthesized by chemical processes. They are considered to be potential building blocks for future nanoscale devices. One particular demonstration is the semiconductor lasers based on high-quality single crystalline nanowires. To get a better understanding of the optical and electronic properties of nanowire lasers, in this presentation, a self-consistent, coupled opto-electronic simulation approach is used to study GaN nanowires. The comprehensive model simultaneously solves the carrier transport equations and photon generation equations self-consistently. It considers the following physical phenomena in GaN nanowires: bulk and surface dark recombination, stimulated and spontaneous emission, anisotropic gain in Wurtzite GaN, modification of the spontaneous emission and spontaneous emission coupling into lasing modes due to microcavity effects, band gap shrinkage due to band renormalization, complex dispersion and reflectivity relations of the guided modes, multiple lateral and longitudinal lasing and non-lasing optical modes. The simulation results provide detailed insight into the influence of surface recombination, size effect of lateral and longitudinal dimensions, lasing and non-lasing mode competition, light versus pumping relations and the "soft" turn-on properties near the lasing threshold, spontaneous and stimulated emission spectra, red-shift of lasing modes, etc. Based on these results, approaches to further enhance the performance of the nanowire lasers will be discussed.

FF11.9
Morphological Study of InN Nanorods Grown by H-MOVPE.
Hyun Jong Park[1], Olga Kryliouk[1], YongSun Won[1], Dmitry Khokhlov[2], Timur Burbaev[3] and Tim Anderson[1]; [1]Chemical Engineering, University of Florida, Gainesville, Florida; [2]Physics Department, Moscow State University, Moscow, Russian Federation; [3]Lebedev Physical Institute, Moscow, Russian Federation.

Interest in InN has recently increased, in part due to recent reports that the value of the band gap energy may be as low as 0.6 eV, which is considerably lower than the previously accepted value of 1.9 eV. Although the value appears to depend on the growth method, material quality, and method of measurement, the fundamental reason for the apparent variation is still unknown. In this work, InN nanorods have been grown at a sufficiently small diameter to minimize the deleterious effects of the substrate on the material quality, but of sufficiently large diameter to neglect quantum confinement effects. The promise of improved structural quality in InN nanorods is that, once nucleated, the ratio of the contact area to free surface area is less than in film growth for the same thickness, thus reducing the strain. This difference and the potential for dislocations to terminate at the sidewalls should significantly improve the structural quality of the material. Hydride-MOVPE (H-MOVPE), a growth technique that generates InCl by reacting TMIn with HCl in a hot-wall reactor, was used to grow InN nanorods. The inclusion of Cl in the system allows growth of InN at relatively low V/III ratio without the formation of In droplets. Furthermore, hydride VPE is known to more easily produce selective area growth. We report the growth of InN nanorods without the use of catalysts or nano-templates. The influence of inlet NH_3/TMIn and HCl/TMIn ratios as well as growth temperature on the nanorod morphology was studied. Nanorods were only grown when NH_3/TMIn ratio is less than 500 in the temperature range 560 to 650 °C. The nanorods for this 1 hr growth were ~1 μm in length with diameter in the range 50 to 380 nm depending on the value of the NH_3/TMIn ratio. At a NH_3/TMIn ratio greater than 10^3, nanorods were not formed, but rather continuous polycrystalline InN films were grown with granular surface morphology. The nanorod average diameter and number density were found to vary significantly with HCl/TMIn ratio in the range 0 to 6. Without adding HCl (hot-wall MOVPE), In droplets formed on top of the InN film. At an HCl/TMIn ratio of 1, InN films with a granular surface morphology were grown, while InN nanorods were developed only at ratios between 2 to 5. The diameter of the rods ranged from 50 to 260 nm depending on the HCl/TMIn ratio. When the HCl/TMIn ratio was 6, the high Cl content reduced the nuclei density, so the number density of InN rods was very low. The growth temperature was varied from 400 to 700 °C. No InN deposition occurred at 400 °C and InN film started to grow from 500 °C. The granular surface morphology was observed from 500 to 550 °C. At 600 °C, InN nanorods were obtained with diameters ranging from 70 to 160 nm. At 700 °C, which is close to the InN decomposition temperature, the number density was greatly reduced. The PL emission at 1.0 eV was observed at room temperature. SEM, GIXD, and AES results will be discussed.

SESSION FF12: Poster Session: Visible LED
Chairs: Juergen Christen and Tsvetanka Jeleva
Tuesday Evening, November 29, 2005
8:00 PM
Exhibition Hall D (Hynes)

FF12.1
Polarization-enhanced ohmic contacts to GaInN-based blue light-emitting diodes.
Thomas Gessmann[1,3], Yangang Xi[2,3], Hong Luo[2,3], Jong-Kyu Kim[1,3], Jinqun Xi[2,3], Kaixuan Chen[2,3] and E. Fred Schubert[1,2,3]; [1]Electrical, Computer, and Systems Engineering, Rensselaer Polytechnic Institute, Troy, New York; [2]Physics, Applied Physics, and Astronomy, Rensselaer Polytechnic Institute, Troy, New York; [3]Future Chips Constellation, Rensselaer Polytechnic Institute, Troy, New York.

Thin p-type Ga1-xInxN cap layers have been grown on p-type GaN contact layers of blue light emitting diodes (LEDs) using metal-organic vapor phase epitaxy (MOVPE) with an AIX 200/4 RF-S reactor. The Ga1-xInxN cap layers have thicknesses smaller than 4 nm and In molar contents varying between x = 0.1 and 0.2. The LED structure consists of a GaN nucleation layer grown on c-oriented sapphire, a 2 μm-thick n-type GaN layer, 5 Ga0.86In0.14N quantum wells embedded in GaN-barriers, and a 0.2 μm-thick p-type GaN layer. Having a cap layer thickness below the critical thickness of Ga1-xInxN on GaN, the piezoelectric field present in the cap layer will result in increased hole tunneling probabilities through the metal-semiconductor barrier. In-content and strain of the GaInN cap layers have been analyzed using high-resolution X-Ray diffractometry. For cap layer thicknesses smaller than 4 nm, pseudomorphic Ga1-xInxN has been obtained for three different In-contents x = 0.1, 0.15 and 0.2. LEDs have been fabricated using photolithograpy processes, CAIBE mesa etching and electron beam deposition of Ni/Au and Ti/Al/Ni/Au contact metals. The specific contact resistance, diode series resistance, ideality factor, forward voltage and optical output power of the LEDs are determined and compared to devices without capping layer. A specific contact resistance ρc = 1.8 x 10-4 Ω cm2 has been obtained for samples with InGaN cap layer; this value is significantly smaller than ρc of a sample without cap layer. The results will be discussed in terms of a model relating the cap layer thickness and In-content to the p-type contact resistance.

FF12.2
Analysis of Quantum Efficiency of GaInN/GaN Light Emitting Diodes in the Range of 420 - 540 nm.
Wei Zhao[1,2], Yufeng Li[1,2], Yong Xia[1,2], Ya Ou[1,2], Mingwei Zhu[1,2], Ibrahim Yilmaz[1,2], Theeradetch Detchprohm[1,2], E. Fred Schubert[1,3] and Christian Wetzel[1,2]; [1]Future Chips Constellation, Rensselaer Polytechnic Institute, Troy, New York; [2]Department of Physics, Applied Physics, and Astronomy, Rensselaer Polytechnic Institute, Troy, New York; [3]Department of Electrical, Computer, and Systems Engineering, Rensselaer Polytechnic Institute, Troy, New York.

Performance of light emitting diodes (LEDs) for the purpose of Solid State Lighting is readily expressed in efficacy and closely related to the external quantum efficiency (EQE). While GaInN/GaN quantum well LEDs have the potential to cover the entire visible light spectrum and the near UV, considerable variation of EQE are generally observed as a function of emission wavelength. In particular the green spectral range (505 - 555 nm) shows a significant lag in emission power characterized by EQE in the range of 10% only. Different from the AlGaInP system used for red LEDs, AlGaInN LEDs exhibit their highest EQE values at very low current densities, typically near 2 - 20 A/cm^2. At the targeted operation conditions for power devices (~ 200 A/cm^2) EQE typically falls to 30 - 50% of its maximum value. Accurate numbers are a strong function of both, the emission wavelength and epitaxy process variations. We have analyzed a large number of LED dies fabricated from over 150 epitaxy runs covering the wavelength range from 420 - 540 nm on a quantitative scale of emission power. AlGaInN LED dies comprising c-axis oriented GaInN/GaN multiple quantum well active layers have been grown by MOCVD on sapphire substrate using low-temperature deposited buffer layers. As a function of drive current we characterize the spectral variations with particular emphasis on the low current range where EQE shows its maximum. We observe two very distinct populations: in the first EQE reaches a maximum of 2 % near 20 A/cm^2 and exhibits only slight reduction towards higher current density; in the second case values of 5 - 7 % are reached near 2 A/cm^2 with a stronger drop towards higher current (Note upon packaging of our die, EQE values typically scale 2-fold and flip-chip processing typically improves EQE by another 25 - 40 %). We correlate this behavior with operation point performance and the epitaxy process development stages. Our full access to the epitaxy and die fabrication process parameters proves critical to a proper interpretation of our findings. Our results allow the definition of specific optimization criteria for the rapid further development of high performance GaInN/GaN LEDs particularly for the green and deep green spectral range.

FF12.3
Blue-Green InGaN/GaN LEDs with Quantum Dot and Quantum Well Structures Grown by Plasma-assisted Molecular Beam Epitaxy.
Tao Xu[1], Jasper S Cabulu[1], Adrian Williams[1], Ryan France[1], Alvin G Stern[1], Theodore D Moustakas[1], Lin Zhou[2] and David J Smith[2]; [1]Department of Electrical and

Computer Engineering, Boston University, Boston, Massachusetts; [2]Center for Solid State Science and Department of Physics and Astronomy, Arizona State University, Tempe, Arizona.

Visible LEDs are based on InGaN multiple quantum wells. It has been observed that the internal quantum efficiency of such devices decreases with the amount of incorporated In. Thus, the currently produced green LEDs have an external quantum efficiency of only 5%. The origin of the monotonic decrease of the LED efficiency from the violet to green is not currently understood. We believe that potential reasons are alloy phenomena related to phase separation and partial long range atomic ordering [1, 2]. The phase separation is the result of the difference in lattice constants between InN and GaN (11%). The long-range atomic order is an alternative mechanism for strain relief. Because the ordered and random alloy domains in the InGaN system have different energy gaps, the partial long-range atomic ordering leads to material with different optical gaps in different parts of the sample. As a result, when electrons and holes are injected either optically or electrically, they become spatially separated and thus unable to recombine efficiently. An additional problem with LEDs based on InGaN alloys grown on foreign substrates, such as sapphire, is the high concentration of dislocations which act as non-radiative recombination centers. In this paper, we report our initial work in addressing these problems. Specifically, we grew LED structures in which we incorporated GaN quantum dots during the nucleation step in order to promote dislocation filtering and annihilation. These quantum dots were grown using Stranski-Krastanov mode of growth. To this point, the active region for the device consists of InGaN quantum wells and work was initiated on designing the active region based on self-assembled InGaN quantum dots. It is well-known that in general quantum dots are free of strain, and thus, one would not expect either phase separation or long-range atomic order to occur since both of these phenomena are strain driven. The details of the nucleation steps on the sapphire substrate involving single layer or multilayer GaN quantum dots will be addressed. Furthermore, the growth and doping of the n- and p- layers of the GaN films as well as formation of the InGaN/GaN multiple quantum wells will be described. Growth of multi-stacks of InGaN quantum dots will be discussed. The devices were fabricated using standard photolithography and metallization schemes and were characterized by measuring the I-V characteristics, electroluminescence spectra and power measurement. [1] Singh, R., D. Doppalapudi, T. D. Moustakas, and L. T. Romano, Appl. Phys. Lett. 70 (9), 1089 (1997). [2] Doppalapudi, D., S. N. Basu, T. D. Moustakas, Journal of Applied Physics, 85(2), 883 (1999)

FF12.4
Light Emitting Diodes Based on InGaN/GaN Quantum Wells Produced by Combining Hydride Vapor Phase Epitaxy and Plasma Assisted Molecular Beam Epitaxy. Jasper Cabalu, Tao Xu, Adrian Williams, Alvin Stern, Ryan France and Theodore Moustakas; Electrical and Computer Engineering, Boston University, Boston, Massachusetts.

There has been significant research and development efforts over the past several years leading to the development of visible and ultraviolet emitters based on the family of III-nitride semiconductors. Much of the work that has been published and applied commercially has been done using metal-organic chemical vapor deposition (MOCVD) as a method of film growth. In this paper, we report on the growth and fabrication of near-ultraviolet to visible light emitting diodes (380 nm to 460 nm), by combining hydride vapor-phase epitaxy (HVPE) and plasma-assisted MBE methods. Thick (10 μm to 40 μm) n+-GaN templates, produced by the HVPE method, were used as substrates for the growth of LED structures by the MBE method. The GaN templates were grown by employing a low temperature (590 ^{o}C) thin GaN buffer and the rest of the film was grown at 1050 ^{o}C. AFM studies on the GaN templates show step-flow growth mode leading to atomically smooth surfaces. The active regions of the LED structures, which consist of InGaN/GaN MQWs, were grown using pulsed nitrogen plasma technique leading to abrupt well and barrier interfaces as confirmed by x-ray diffraction (XRD) measurements. Using this method, we obtained InGaN/GaN MQWs whose room temperature photoluminescence (PL) spectra have a full width at half maximum (FWHM) of 12 nm (105 meV). Large and small area mesa devices were fabricated using conventional optical lithography and were designed for topside as well as backside light extraction. Finger-type mesa design was also incorporated to sufficiently increase current spreading. The LEDs were semi-packaged onto transistor outlines as a bare die or flip-chip bonded configuration to address issues related to heat dissipation. These devices were characterized under pulsed and continuous mode operation and their optical power was measured using a calibrated integrating sphere. The growth and fabrication of these devices was preceded by detailed growth and doping studies of the various layers of the LED structure. These include detailed nucleation studies on (0001) sapphire substrates as well as identification of kinetic factors which lead to good crystalline-quality InGaN alloys.

FF12.5
Characterization of Photonic Bandgap Crystals using Angular Scatterometry. Tom Ryan, Christopher Raymond and Steve Hummel; Accent Optical Technologies, Bend, Oregon.

Photonic bandgap crystals (PBCs) have found recent applications in the field of high brightness light emitting diodes (HBLEDs). By using a PBC in conjunction with an HBLED, significant improvements in light extraction efficiency and better directionality [1] have been reported. Given this value and the drive for more efficient HBLEDs for solid state lighting applications, PBCs have a future in HBLEDs. But the manufacture of a PBC is not straightforward. The dimensions and shape of the PBC must be well-controlled if the increase in efficiency or directionality is to be realized. Therefore, control of the PBC manufacturing process is critical to the device performance, and a metrology for PBCs is needed. Scatterometry is an optical metrology based on the measurement and analysis of light scattered from a periodic surface. In contrast to classic scatterometry which is concerned with the measurement of surface roughness or singular defects on some planar surface, the scatterometry discussed here is applicable to periodic diffracting features, such as line-space gratings that are formed in photoresist and silicon during the fabrication of semiconductor devices. Because it is rapid, non-destructive and has excellent precision, scatterometry is being used today in a wide variety of high volume silicon manufacturing applications. In this work, we report on the use of angular scatterometry for the measurement of PBCs. We begin with an overview of scatterometry technology, including the hardware used to measure an angular scatterometry "signature," and the analysis methods for determining measurement results. Then, through theoretical simulations of real PBC structures, we will demonstrate and quantify the sensitivity of angular scatterometry for characterizing PBCs. We will show how angular scatterometry can uniquely measure several variables of the PBC structure, including lateral dimensions, thickness, sidewall angle and even overall shape. Based on knowledge of the noise spectra of an angular scatterometer, we will provide estimates of the expected precision of such measurements. Finally, considerations for measurements of real PBCs in a manufacturing environment will be discussed. 1. J. J. Wierer et al, "III-Nitride LEDs with photonic crystal structures," Proc SPIE 5739, pp. 102-107, Mar 2005.

FF12.6
Abstract Withdrawn

FF12.7
The Optical Power of GaN-based Diodes Enhanced by Bias-Assisted Photoelectrochemical Etching Process.
Kwang-Woo Kwon[1,4], Young-Ho Kim[1], Sun-Hong Park[2], Soo-young Seo[2], Seon-Hyo Kim[2], Kyoung-Bo Kim[4] and Sang-Wook Han[3]; [1]Material Sci. & Eng., Hanyang University, Seoul, South Korea; [2]Material Sci. & Eng, Postech, Pohang, South Korea; [3]Education of Science, Chonbuk National University, Jeon-ju, South Korea; [4]Ninex, Pyoung-taek, South Korea.

We present the optical power improvement of GaN-based light emitting diodes (LED). The diodes of p-GaN/active layer/n-GaN were fabricated on sapphire substrates with a metal-organic chemical vapor phase deposition. First, a mesa-mask process was applied to the p-GaN/active layer/n-GaN to partially remove the p-GaN/active layer and to expose the part of n-GaN layer. Consecutively, a bias-assisted photoelectrochemical (PEC) etching process was applied to the exposed n-GaN layer to create a bumpy n-GaN surface. With the simple etching processes, the light emitting power of the GaN LEDs was improved by twice. The surface morphology of etched n-GaN LED structure was studied with field emission scanning electron microscopy (FE-SEM). The FE-SEM images showed that pores with relatively uniform size were randomly spread over whole surface of the n-GaN layer. The density and size of pores could be controlled by KOH solution and etching time. When the photons radiated from the active layer travel into the n-GaN layer, a large number of the photons are trapped in the n-GaN layer due to internal reflections by smooth interfaces of n-GaN/air and n-GaN/Al2O3. The surface morphology of n-GaN layer could change the internal reflection of the light so that more photons can escape from the n-GaN layer with a rough surface. We will discuss the effect of the surface morphology on the light emitting powder.

FF12.8
Electrical Characterization of Blue Light Emitting Diodes as a Function of Temperature. Madhu Murthy[1], Michael A. Awaah[1], Kumar K Das[1], Derek Wang[2], M Park[2] and F. J. Walker[3]; [1]Electrical Engineering, Tuskegee University, Tuskegee, Alabama; [2]Department of Physics, Auburn University, Auburn, Alabama; [3]ORNL/University of Tennessee, ORNL/University of Tennessee, Oak Ridge, Tennessee.

Blue light emitting diodes (LEDs) based on an AlGaN/GaN/AlGaN double heterjunction structure were electrically characterized as a function of temperature. Current-voltage (I-V), capacitance-voltage (C-V) and reverse recovery storage time measurements were conducted at temperatures in the range between -8o and 75o C. Capacitance-voltage measurements as a function frequency and electroluminescence study at room temperature were also performed. As reported previously, from room temperature I-V measurements these LEDs appeared highly non-ideal, as evidenced by high values of the ideality factor obtained from semilogaritmic plots of the forward characteristics. However, logarithmic plots were interpreted to be due to space charge limited current (SCLC) conduction through the active region of the LEDs in the presence of deep level states. Several deep-levels with concentrations of the order of 1017/cm3 were identified from observed changes in the slope of the logarithmic plots. Present electroluminescence data indicate that the major peak observed at 430 nm corresponds to a transition from the conduction band minimum to one of these levels identified from the SCLC, located at 0.52 eV above the valence band maximum. It was observed that the diode turn-on voltage decreased with increasing temperature, however, reverse leakage currents monitored at -1, -5 and -10 V increased only by a small amount with increasing temperature, corresponding Arrhenius plots yielded very low activation energies, in comparison Si and GaAs p-n junction diodes yield an activation energy of approximately Eg/2. The recombination lifetimes as calculated from experimentally determined reverse recovery storage times remained constant over the entire range of temperature. Again, in the case of Si diodes a small variation in the recombination lifetime with temperature is observed, however, according to a previously a published study, in some cases Si diodes yield an activation energy that corresponds to the deep state responsible for the recombination process. Diode capacitance was measured as a function of frequency between 20 Hz and 1Mhz, for a bias level between -2.5 and 2.5 V at an interval of 0.5 V. For each bias level at low measurement frequencies a higher capacitance was observed, at about 5 kHz the capacitance gradually dropped a to low value and remained constant to 1 MHz. A loss peak centered about 5 kHz was observed in the corresponding plot of as a function of frequency, f. This peak appears to arise from mid-gap states in the depletion region. A detailed analysis of the data will be presented.

FF12.9

Study of GaN Light-Emitting Diodes Obtained by Laser-Assisted Debonding. C. P. Chan[1], T. M. Yue[2], C. Surya[1], A. B. Djurisic[3], C. K. Liu[4] and M. Li[4]; [1]Department of Electronic and Information Engineering and Photonics Research Centre, The Hong Kong Polytechnic University, Hong Kong, Hong Kong; [2]Department of Industrial and Systems Engineering and Advanced Manufacturing Technology Research Center, The Hong Kong Polytechnic University, Hong Kong, Hong Kong; [3]Department of Physics, The University of Hong Kong, Hong Kong, Hong Kong; [4]ASM Pacific Technology Limited, Hong Kong, Hong Kong.

Gallium nitride (GaN) based blue light-emitting diodes (LED), grown by metaloragnic chemical vapour deposition and prefabricated on sapphire growth substrates, were separated from the sapphire using KrF excimer laser processing. The LED was first bonded on an intrinsic Si substrate using gold studs thermosonic flip chip bonding processing. A single laser pulse at 248 nm wavelength (25 ns pulse length) with fluence of 0.5 J/cm^2 irradiated through the transparent sapphire, yielding a debonded GaN membrane bonded on Si. The debonded GaN LED was then etched by potassium hydroxide (KOH) solution to roughen the surface of the debonded GaN layer. The roughed surface reduces the light loss due to high refractive index of GaN and enhances photons extraction. Atomic Force Microscopy (AFM) measurements and thermal analysis were used to characterise the laser debonded LEDs. Light output power as a function of injection current at different surface roughness are also reported.

FF12.10

Optimization of Ridge Wave Guide GaN-based Homo-Epitaxial Laser Diodes. Jens Dennemarck, Stephan Figge and Detlef Hommel; Institute of Solid State Physics, Bremen, Germany.

Light emitting devices in the blue-UV spectral region are nowadays fabricated on basis of group-III-nitrides due to the wide band gap of these materials. In most cases they are grown by hetero epitaxy on substrates as Al2O3 or SiC. In contrast homoepitaxy has a lot of advantages as reduced defect density, less strain and it enables a different technology approach such as cleaveable facets and backside contacts. However from high importance is still the design of the ridge wave guide structure, because of the lateral optical confinement. The aim of this paper is the analysis of different technology processes, at which the characteristics of blue GaN/InGaN-based LD's is shown. The samples are grown homoepitaxial by MOVPE on Lumilog laser-grade GaN substrates. Two approaches for the investigation of the ridge wave guide structure have been realized. On the one hand the width of the injection stripe was varied and on the other hand different etch depths for the ridge have been chosen. Clear dependencies on the different structures could be found. The stripe width was varied from 10mu to 2mu. The smaller the stripe width the better the performance of the device in sense of threshold current density. For the second approach three different types of samples have been processed: planar structures, where no semiconductor material is etched and where the insulator is directly deposited on the p-doped GaN layer, a ridge structure etched down to the waveguide on p-side of the device and another ridge structure, where the ridge is etched through the quantum well into the lower waveguide. The last sample with largest etch depth showed the best thermal and mechanical stability although a thicker insulator deposition is necessary in this case which might induce strain in the structure. Compared to the other structures, which have threshold current densities of 10-15kA/cm$\hat{2}$, for this devices lasing was achieved at $\sim$5kA/cm$\hat{2}$. Because of this a much higher duty cycle of up to 50% could be applied in contrast to the 10% in case of the planar structures. One drawback in the homoepitaxy of LD's is a parasitic waveguiding in the GaN substrate. This is visible in the far field as a dominant emission of a parabolic shape. In the case of the deeply etched ridge wave-guide structure it was possible to achieve a better confinement, as seen in a change of the far field pattern.

FF12.11

Role of deep levels in DC current aging of GaN/InGaN Light-Emitting Diodes studied by Capacitance and Photocurrent Spectroscopy. Anna Cavallini[1], Antonio Castaldini[1], Lorenzo Rigutti[1], Gaudenzio Meneghesso[2], Matteo Meneghini[2], Simone Levada[2], Enrico Zanoni[2], Ulrich Zehnder[3], Thomas Zahner[3] and Volker Haerle[3]; [1]Physics, University of Bologna, Bologna, Italy; [2]Information Engineering, University of Padova, Padova, Italy; [3]OSRAM Opto Semiconductors, Regensburg, Germany.

We present a combined Capacitance-Voltage (C-V), Deep Level Transient Spectroscopy (DLTS) and Photocurrent (PC) study of short-term instabilities of InGaN/GaN LEDs submitted to forward current aging tests at room temperature. C-V profiles detect changes consisting in apparent doping and/or charge concentration increase within the quantum wells. This increase is correlated to dramatic modifications in the DLTS spectrum when the reverse bias and filling pulse are properly adjusted in order to probe the quantum well region. The new distribution of the electronic levels detected by DLTS could explain the observed decrease in the light emission efficiency [1] of the device, as the deep levels generated during the stress may provide alternative recombination paths for free carriers. The photocurrent spectra do not change in shape during stress, although their amplitude slightly decreases. This is related to a decrease of the device yield, in this photodetector configuration, with increasing aging time, although with a slower rate than the modifications monitored by DLTS. Thus, we can suggest that the introduction of new defect levels in the bulk material lowers the free carrier mobility. [1] A.Castaldini et al., phys. stat. sol. (c), 2, No. 7 (2005), p. 2862

FF12.12

3D Simulations on Realistic GaN-Based Light-Emitting Diodes. Z. Q. Leo Li, Oleksiy Shmatov and Simon Li; Crosslight Software Inc., Burnaby, British Columbia, Canada.

Comprehensive multiscale models have been employed to simulate the realistic GaN based light-emitting diodes (LED) using 3D finite-element analysis.The advanced features include drift-diffusion model for carrier transport, self-consistent Poison-Shrodinger and K.P models for multi-quantum well band structure, quantum tunneling model for heterojunction,spontaneous and piezoelectric polarization models for built-in electric field,heat flow model for self-heating and ray-tracing model for photon extraction. All the advanced capabilities have been integrated into our software APSYS[1].In this paper, we present the 3D simulations on the quaternary AlGaInN LED with an emission wavelength of approximately 360 nm. Based on the detailed simulation results, we were able to analyze the impact of micro- and nanoscale physical effects such as current crowding, carrier leakage, built-in interface charge and self-heating on the internal efficency of the device. The macroscale effect of the geometry on photon extraction was analyzed using 3D ray-tracing and photon recycling techniques. Results of different stuctures will be given to demonstrate the power of the software in handling complicated realistic LED geometries. The simulation results can be used to optimize the design of quantum well layers, blocking layer materials and electrode geometries etc. [1] APSYS 2005.03, Crosslight Software Inc, (http://www.crosslight.com)

SESSION FF13: Poster Session:
Sensor/Detector/Electronic Devices
Chairs: Juergen Christen and Tsvetanka Jeleva
Tuesday Evening, November 29, 2005
8:00 PM
Exhibition Hall D (Hynes)

FF13.1
Application of Aluminum Nitride Thin Film for Micromachined Ultrasonic Transducers. Qianghua Wang, Jianzeng Xu, Changhe Huang and Gregory Auner; Department of Electrical and Comouter engineering, Wayne State University, Detroit, Michigan.

This paper reports the fabrication and characterization of micromachined ultrasonic transducers (MUT) based on aluminum nitride (AlN) thin films. The AlN thin film grown in plasma source molecular beam epitaxy (PSMBE) system was sandwiched by two aluminum metal layers deposited on a Si(100) substrate. Relative low temperature growth (<450 °C) was adopted to make the process compatible with IC or MEMS technology. X-ray diffraction shows the films are highly textured with a c-plane orientation, which ensures an excellent piezoelectric property. Piezoelectric MUTs were prepared using the Al/AlN/Al sandwich structure on a silicon diaphragm. Electrical impedances of MUT devices were systematically evaluated as a function of frequency. Fundamental resonance frequencies of MUTs were determined in the range from 65 kHz to 75 kHz. Effective coupling factors of the devices were calculated as ∼0.18 from the resonance and antiresonance frequencies in the impedance spectra.

FF13.2
Fabrication of Schottky-Type UV Photodetectors based on Bulk GaN. Yi Zhou[1], Dake Wang[1], Chin-Che Tin[1], John Williams[1], Minseo Park[1], N. Mark Williams[2] and Andrew Hanser[2]; [1]Department of Physics, Auburn University, Auburn, Alabama; [2]Kyma Technologies, Inc., Raleigh, North Carolina.

In the case of a conventional Schottky UV photodetector, electrons are transported laterally across the dislocation line, deteriorating the performance of photodetector operation. An alternative route to alleviate this problem is to use a vertical device structure which harnesses "dislocation-blind" carrier transport. An improved photodetector characteristics has been reported from the device that uses vertical transport. However, this device employs front ohmic contact which requires mesa etching of the device, resulting in generation of defects due to ion damage. With the advent of single crystal GaN wafers, the vertical UV photodetectors with frontside Schottky and backside ohmic contacts can be produced. The low background electron concentration will also ensure a formation of a viable Schottky contact, reducing the dark current. In the present investigation, Schottky-type UV photodetectors were fabricated using bulk GaN with a low background electron concentration (<10î6 cm-3). The Schottky photodetector was fabricated using Pt and Ti/Al as Schottky and ohmic contacts, respectively. The devices exhibited an excellent UV/visible contrast. The device characteristics of the photodetectors are further being investigated, and the results will be presented at the meeting. The structure of the device is being optimized in order to enhance quantum efficiency and reduce a dark current.

FF13.3
Schottky Diodes for Hydrogen Sensing on Free-standing GaN. Lars Voss[1], Hung-ta Wang[2], S. J. Pearton[1], F. Ren[2] and B. P. Gila[1]; [1]Materials Science and Engineering, University of Florida, Gainesville, Florida; [2]Chemical Engineering, University of Florida, Gainesville, Florida.

Pd and Pt schottky diodes were fabricated on free standing n-GaN and characterized for their response to hydrogren as a function of temperature and concentration. Vertical and lateral diodes were both fabricated and characterized for a variety of diameters. Even at room temperature, diodes display a large increase of over 15 mA upon introduction of 500 ppm hydrogen. Change is rapid upon introduction of hydrogen. The devices recover to their initial state upon exposure to air. Increased temperature increases the sensitivity of the devices. Rapid response for sensing concentrations to at least 10 ppm at room temperature has been demonstrated to be possible for Pt based devices, with somewhat worse performance for Pd based devices.

FF13.4
Mechanism of Current Leakage in Ni Schottky Diodes on Cubic GaN and $Al_xGa_{1-x}N$ Epilayers. Donat J. As[1], Stefan Potthast[1], Jara Fernandez[1], Klaus Lischka[1], Hiroyuki Nagasawa[2] and Masayuki Abe[2]; [1]Department of Physics, University of Paderborn, Paderborn, Germany; [2]HOYA Advanced Semiconductor Technologies Co., Ltd., Kanagawa, Japan.

Ni Schottky-diodes (SDs) 300 μm in diameter were fabricated by thermal evaporation using contact lithography on cubic GaN and AlxGa1-xN epilayers. Phase-pure cubic GaN and c-Al0.3Ga0.7N/GaN structures were grown by plasma assisted molecular beam epitaxy (MBE) [1] on 200 μm thick free-standing 3C-SiC (100) substrates, which were produced by HAST [2]. The quality of the cubic group III-nitride epilayers was checked by high resolution X-ray diffractometry, atomic force microscopy and photoluminescence at room temperature and at 2 K. Large deviations from the thermionic emission transport were observed in the current voltage (I-V) behavior of these SDs. Detailed analysis of the I-V characteristics at 300 K and at low temperature showed that a thin surface barrier is formed at the Ni semiconductor interface [3]. Thermal annealing in air at 200°C alters the composition of this thin surface barrier and reduces the leakage current by three orders of magnitude. The doping density dependence of breakdown voltages derived from the reverse breakdown voltage characteristics of c-GaN SDs is in good agreement with theoretically calculated values and follows the expected trend [4]. From these experimental data a blocking voltage of higher than 600 V is extrapolated for c-GaN films with a doping level of $N_D = 5x10^{15}$ cm^{-3}. [1] D.J. As, in "Optoelectronic Properties of Semiconductors and Superlattices" Vol. 19, 323 (2003) [2] H. Nagasawa et al., Silicon Carbide, Springer-Verlag, 207 (2003) [3] H. Hasegawa et al., J. Vac. Sci. Technol. B 20, 1647 (2002) [4] K. Matocha et al., Mat. Sci. Forum 389-393, 1531 (2002)

FF13.5
Simulation of Self-Heating and Ambient Temperature Effects in GaN-based Field-Effect Transistors. Valentin O. Turin and Alexander A. Balandin; Nano Device Laboratory, Department of Electrical Engineering, University of California Riverside, Riverside, California.

GaN-based field-effect transistors (FETs) are promising candidates for the ultra-high-power microwave systems, power electronics and high temperature applications. Due to the high power densities involved and significant thermal resistance of the GaN device structure self-heating effects present a major problem. In this work we report results of the electro-thermal drift-diffusion simulations of GaN metal-semiconductor field effect transistors (MESFET) on SiC and sapphire substrates. The simulations were performed using commercial ISE TCAD DESSIS software with the model for the high-field electron mobility developed by us. The proposed modified transferred-electron model is capable of capturing the specifics of the electric field dependence of the electron drift velocity in GaN such as a pronounced kink in the low-field region and a peak in the high-field region. The issues of numerical modeling, including the required size of the simulation domain for accurate electro-thermal simulations, have also been studied. For this purpose the equation of heat diffusion in a transistor structure has been solved analytically using the image method. The cases of the point and linear heat sources are considered for a schematic transistor structure over a wide range of ratios between the thermal conductivity of a substrate and a heat sink material. Using the developed models, we carried out simulations of GaN MESFET to obtain the hot spot temperature, negative differential resistance and transconductance dependence on the substrate size. We studied the influence of ambient temperature and an extra thermal resistance, which imitated the transistor packaging. The modeling results are compared with the experimental data obtained in the NDL. The possibility of the thermal breakdown as a failure mechanism in GaN transistors will also be discussed. The developed models and obtained simulation results can be used for the layout optimization of GaN FETs as well as for other high-power and high-temperature electronics devises. This work has been supported in part by the ONR award to A.A.B.

FF13.6
Double-Ion-Implanted GaN MESFETs with Extremely Low Source/Drain Resistance. Kazuki Nomoto[1], Nobuyuki Ito[1], Taku Tajima[1], Takeshi Kasai[2], Tomoyoshi Mishima[3], Taroh Inada[1], Masataka Satoh[1] and Tohru Nakamura[1]; [1]Department of EECE and Research Center of Ion Beam Technology, HOSEI University, Koganei, Tokyo, Japan; [2]Chemitronics, Musashimurayama, Tokyo, Japan; [3]Hitachi Cable, Tuchiura, Ibaraki, Japan.

Ion Implantation is one of the most indispensable technologies for impurity doping especially in Silicon based integrated circuits. However, a few reports are published on application of ion implantation to the active regions except for isolation in GaN devices, because the complicated technologies such as hot ion implantation are needed to prevent damage induced by ion implantation. The activation and crystal damage recovery of implanted GaN also require annealing at temperatures above 1500 ^oC. We demonstrate novel double-ion-implanted (DII) GaN MESFETs with extremely low on-resistance, which is defined as the slope of the linear region of the Id-Vds curves. Silicon ions were implanted into channel and source/drain regions on GaN/Al $_2O_3$ substrates at room temperature,

and high activation rates were achieved at temperature below 1200 ^{o}C. A 2 μm thick undoped GaN was grown on a sapphire substrate by MOVPE. Silicon ions are implanted into channel and source/drain regions on GaN/Al_2O_3 substrate at doses of 5 x 10^{12} cm^{-2} and 1 x 10^{15} cm^{-2} at energies of 150 keV and 80 keV through a 50 nm thick SiN_x layers deposited by PECVD, respectively. High electrical activation rate of 60 % for implanted silicon was obtained by annealing at the temperature as low as 1200 ^{o}C for 2 min in N_2 ambient. The SiN_x layer was removed using diluted HF and a SiN_x layer for surface passivation was deposited again by PECVD. Source/drain ohmic contacts were formed by depositing Ti/Al (50/200 nm) layers, followed by an annealing at 600 ^{o}C for 3 min in N_2 ambient. The low ohmic contact resistance as low as 2 x 10^{-8} ohm·cm^2 was measured using circular transmission line method (C-TLM). Finally, gate schottky contacts were formed by depositing Ni/Al (50/100 nm) layers. Devices with 5 μm gate length and 175 μm gate width were tested. Gate-source and gate-drain spacing were 5 μm. DC characteristics of DII and ion-implanted-channel MESFETs were measured. Maximum drain current (Idss) of 42 mA/mm at Vg= 0 V and Vds= 15 V and maximum transconductance (gm_{MAX}) of 9 mS/mm were obtained for DII MESFETs, while those of ion-implanted-channel MESFETs without heavily doped source/drain regions were 24 mA/mm and 3 mS/mm, respectively. Idss increased to 200 mA/mm and gm_{MAX} to 30 mS/mm, when gate length reduced to 2 μm for DII MESFETs. Low source/drain resistance of 4.9 ohm·mm was obtained for DII MESFETs, whereas 72 ohm·mm for ion-implanted-channel MESFET. This means that reduced source/drain resistance causes increase of Idss and gm. We have demonstrated DII MESFETs to improve DC characteristics, especially on-resistance. DII MESFETs show comparable DC performance to the ion implanted channel MESFETs with 175 % increase of Idss, 300 % increase gm and 94 % decrease of source/drain resistance. Significant performance of MESFETs could be realized by reducing parasitic resistance by ion implantation.

FF13.7

Electrical domains and sub-millimeter signal generation in AlGaN/GaN superlattices. Irina Gordion[1], Alexander Manasson[2] and Vladimir Litvinov[1]; [1]WaveBand Corporation, Irvine, California; [2]Physics Department, University of Michigan, Ann Arbor, Michigan.

We discuss the feasibility of a sub-millimeter wave source based on AlGaN/GaN superlattices. Negative differential conductivity, electrical domain formation, current oscillations, and power efficiency of a perspective source are studied with the Atlas-Silvaco semiconductor device simulator. We relate the superlattice geometry and conduction band profile, distorted by the polarization fields, to the oscillation frequency and power efficiency of the device. We also determine the optimal Al content, superlattice period, and parameters of the lump-element external circuit that favor sub-millimeter wave generation. The spectral content of the output signal depends on impedance matching and the main harmonic is tunable by applied voltage and series resistance. Almost sinusoidal output at 450 GHz can be achieved by a proper impedance matching. Device operation at higher output frequency requires the more precise matching between a superlattice and an external resonant circuit and the increase in frequency occurs at the cost of power efficiency.

FF13.8

Growth, processing and characterization of GaN/AlGaN/SiC vertical n-p diodes. Steven Boeykens[1,2], Maarten Leys[1], Marianne Germain[1], Jef Poortmans[1], Ronnie Belmans[2] and Gustaaf Borghs[1]; [1]IMEC, Leuven, Belgium; [2]Dept. of Electrical Engineering, Katholieke Universiteit Leuven, Leuven, Belgium.

Growth of III-V nitrides is essentially done either on sapphire or on 6H- and 4H-SiC. SiC crystals show advantages for the hetero-epitaxial growth of GaN, including better lattice matching, higher thermal conductivity, and electrical conductivity. This latter characteristic offers interesting perspectives in the development of vertical III-Nitride devices for switching purposes. As an example, the GaN layer in a SiC/GaN heterojunction could be a wide band gap emitter in Heterojunction Bipolar Transistors. It is thus worthwhile investigating the growth of GaN layers on 4H-SiC substrates, which require $Al_xGa_{1-x}N$ nucleation layers. For electrical conduction, maximum doping level is required, and additionally the Al content should not exceed 40%. In this work, growth of GaN on conductive AlGaN nucleation layers on 4H-SiC is investigated in order to obtain high quality epitaxial structures for vertical transport devices. All layers are grown using LP-MOVPE in a 3x2// vertical close-coupled showerhead Thomas Swan reactor. The structural quality and electrical properties have been investigated using HR-XRD, I-V-T and C-V measurements. Two different p-type 4H-SiC substrates were used: on-axis with a doping level of 2x10^{18} cm^{-3} and 8° off-oriented with doping level of 1x10^{18} cm^{-3}, as given by the manufacturer. Two different n-type doped AlGaN (10^{19} cm^{-3}) nucleation layers were used: a 240 nm 30 % AlGaN layer and a 300 nm 8% AlGaN layer. On top of these nucleation layers, a 300 nm n-type doped GaN layer (2x10^{18} cm^{-3}) was grown. The GaN/AlGaN layers were patterned and mesa structures were etched using a Cl_2-based RIE etching process. Ohmic contacts were applied on the n-type GaN using a Ti/Al/Mo/Au metallisation scheme with RTA at 750°C. On the backside of the p-type 4H-SiC substrate, a Ti/Al metal stack annealed at 1025°C was used as Ohmic contact. Ideality factors for the diodes range from 1.5 to 1.8 with corresponding saturation current densities of 1.5x10^{-24} A/cm^{-2} to 2x10^{-21} A/cm^{-2}. From thermal I-V measurements, activation energies of the saturation current densities could be extracted to be 1.60 - 1.65 eV. As this corresponds to a mid-gap level, it can be concluded that recombination processes, rather than drift-diffusion, govern the transport mechanism of these diodes. C-V measurements on these diodes indicate a built-in voltage of 2.5 - 2.7 V. The resulting conduction band offsets range from 0.4 eV to 0.6 eV, showing little variation with Al concentration. Also, the degree of misorientation of the substrate does not seem to play a role. It is most likely that many defect states exist at the AlGaN/SiC interface. At present, further work is carried out to improve this interface quality. This improvement is necessary for the GaN/SiC HBT to fulfill the theoretical predictions in terms of performance.

FF13.9

Fabrication and device characteristics of bulk GaN-based Schottky diodes. Yi Zhou[1], Mingyu Li[1], Dake Wang[1], Claude Ahyi[1], Chin-Che Tin[1], John Williams[1], Minseo Park[1], N. Mark Williams[2] and Andrew Hanser[2]; [1]Department of Physics, Auburn University, Auburn, Alabama; [2]Kyma Technologies, Inc., Raleigh, North Carolina.

Gallium nitride (GaN) has been considered as an important material for high power electronics. GaN-based Schottky diode has been fabricated using GaN epitaxially grown on foreign substrates. However, relatively little work has been performed on fabrication of Schottky diode that utilizes bulk GaN wafer. In this investigation, a Schottky diode was fabricated using a bulk n–GaN wafer produced by Kyma Technologies, Inc. Schottky and ohmic contacts were prepared on the Ga- and N-faces of the bulk GaN using Pt and Ti/Al, respectively. Without any edge-termination scheme, a relatively high breakdown field (5.46 kV/cm) was achieved. As is expected, the breakdown field decreases as the device size increases. It appears that the high breakdown field of the device is attributed to a low background electron concentration of the bulk GaN (<101̂6 cm-3). The Schottky diode also showed an extremely short switching speed (< 20 ns).

FF13.10

Reduction of Base Access Resistance in AlGaN/GaN Heterojunction Bipolar Transistors using GaInN Base Cap Layer and Selective Epitaxial Growth. Jay M. Shah[1], J. K. Kim[1], Y. Xi[2], Th. Gessmann[1] and E. F. Schubert[1,2]; [1]Department of Electrical, Computer, & Systems Engineering, Rensselaer Polytechnic Institute, Troy, New York; [2]Department of Physics, Applied Physics, & Astronomy, Rensselaer Polytechnic Institute, Troy, New York.

One of the major challenges affecting the performance of AlGaN/GaN heterojunction bipolar transistors (HBTs) is the high base access resistance of the p-type GaN base. A novel concept is proposed to reduce the base access resistance and the base surface recombination current in AlGaN/GaN HBTs by employing a strained GaInN cap layer and selective epitaxial growth (SEG). The unipolar heterojunction formed by a strained GaInN layer and GaN results in a 2-dimensional hole gas (2DHG) at the interface due to strain-induced and polarization fields in III-V nitride materials. Such polarization enhanced contacts have been reported to have excellent ohmic characteristics when compared to conventional contacts to GaN [1]. Although GaInN cap layers have been used to reduce the contact resistance in GaN/GaInN HBTs [2], they do not reduce the high base access resistance in AlGaN/GaN HBTs. We propose a new design in which, the lateral current flow in the p-type base is realized by the 2DHG obtained by employing a GaInN cap layer on GaN base and SEG of the base and the emitter. Along with reducing the base contact resistance, this technique significantly reduces the base access resistance and the exposed base surface, which results in a lower base surface recombination current. Such a structure would enable better performance of AlGaN/GaN HBTs in terms of higher current gain and a lower offset voltage. Experimental results on as-grown p-type GaN base indicate an rms surface roughness of 0.7 nm measured by atomic force microscopy (AFM). Dry etching of p-type GaN base, using chemically assisted ion beam etching (CAIBE) at beam energies of 600 eV and 400 eV, resulted in rms surface roughness of 7.2 nm and 4.5 nm, respectively. This indicates that a low energy dry etch using CAIBE renders a surface suitable for SEG of p-type GaN base, which reduces the effect of base etch damage and results in a lower defect density at the base-emitter junction. REFERENCES: [1] T. Gessmann, J. W. Graff, Y.-L. Li, E. L. Waldron, and E. F. Schubert,

J.Appl.Phys. **92**, 3740 (2002) [2] T. Makimoto, K. Kumakura, and N. Kobayashi, *Jpn.J.Appl.Phys.* **43, 1922(2004)**

FF13.11
Quaternary Thermodynamic Stability of Oxide Dielectrics to III-N Semiconductors. Mark Johnson and Yoga N. Saripalli; Materials Science and Engineering, NC State University, Raleigh, North Carolina.

III-Nitride electronic device fabrication such as high-speed field effect transistors (FETs) motivates the development of electrically insulating oxide dielectrics on semiconductors. Of specific interest are oxide-semiconductor structures which have a low-density of unfilled interface states, enabling a metal-oxide semiconductor (MOS) layers with an unpinned Fermi level. In our research, we have examined the fabrication of MOSFET devices using GaN semiconductor channel structures with oxide dielectric layers epitaxially deposited by molecular beam epitaxy. The GaN channel structures are deposited by metal-organic chemical vapor deposition (MOCVD). The electrical properties of the fabricated MOS structures depends on structural and chemical factors including the bandgap energy, band offset energies, lattice misfit across the MOS interface which induce extended defects, and dielectric constant. Of particular importance is the thermodynamic stability of the III-N to Metal-Oxide interface to avoid the unwanted formation of secondary phases. As such, the application of macroscopic thermodynamic phase diagrams can be a useful tool for the identification and selection of dielectric materials. For example, it has been long reported that for traditional III-V semiconductors such as GaAs, either Ga_2O_3 or As_2O_3 can be formed in thermodynamic equilibrium, leading to undesired bond configuration and a high density of interface states. For GaN, nitrous-oxide compounds are volatile providing a path for stable oxide-nitride anion interface formation with only a Ga_2O_3 phase on the semiconductor surface. However an epitaxial dielectic requires two interfaces to a compound semiconductor, one for each of the anion and cation sub-lattices. Combined structure such as the 200nm GaN / 2nm Ga_2O_3 / 16nm Gd_2O_3 epitaxial dielectric test system we have examined requires Ga-N-O-Gd quaternary thermodynamic stability. To identify additional candidate dielectrics for compatibility with GaN, we apply general requirements of thermodynamic stability across the III-N-O-metal quaternary phase diagrams. In this paper, we report on the quaternary phase stability of: Ga-N-O-Mg (MgO); Ga-N-O-Ca (CaO); Ga-N-O-Zn (ZnO); Ga-N-O-Sr (SrO); Ga-N-O-Hf (HfO_2); Ga-N-O-Sc (Sc_2O_3); and Ga-N-O-Y (Y_2O_3) quaternary systems using known and calculated thermochemical data to identify candidate MOS dielectrics for GaN. Based on this assessment we have identified epitaxially deposited dielectrics for GaN MOSFET fabrication which should exhibit thermal stability and avoid unwanted equilibrium phase formation at the semiconductor-oxide interface.

FF13.12
Design and Development of MBE Grown AlGaN/ GaN HEMT Devices on SiC Substrates for RF Applications.
Ashok K. Sood[1], Rajwinder Singh[1], Yash R. Puri[1], Frederick W. Clarke[2], Amir Dabiran[3], Peter Chow[3], Jie Deng[4] and James C. M. Hwang[4]; [1]Magnolia Optical Technologies, Inc., Woburn, Massachusetts; [2]U. S. Army Space and Missile Defense Command, Huntsville, Alabama; [3]SVT Associates, Inc., Eden Prairie, Minnesota; [4]Electrical Engineering, Lehigh University, Bethlehem, Pennsylvania.

AlGaN/ GaN based devices have demonstrated versatility for RF electronic applications, which is practically unmatched by any other material system for Military and Commercial applications (1,2). AlGaN/ GaN HEMT device structure that incorporates an innovative HEMT design has the promise of high performance and reliability (3). Our HEMT design approach includes growth of AlN buffer layer followed by growth of AlGaN layers on lattice matched semi-insulating 6H-SiC Substrates. In this paper, we will present our modeling and simulation for the AlGaN HEMT device. The model includes Piezoelectric and spontaneous polarization effects on GaN/AlGaN interface and simulated by fixed sheet charge. Two dimensional (2D) physical device model of AlGaN HEMT is constructed and simulated using Silvaco Atlas program. Simulated DC characteristics of the AlGaN HEMT structure will be presented along with the figures of merit for different Al concentration. The HEMT device structures were grown using RF Plasma Assisted MBE Technique. This approach has demonstrated very uniform epitaxial layers with high mobility. Key to high quality HEMT structures is the ability to grow AlN Buffer layers. Details of the electrical and optical characteristics of the layers will be presented. To address the uniformity and improvement of performance variations, fabrication of these devices includes a dry-etching technique that has the potential of reducing the etch damage to the HEMT structure (4), and improving the reliability of the devices. An inductively coupled plasma (ICP) Reactor is employed for fabricating the HEMT devices. Details of the ICP Process will be presented. We will also present results on the fabricated HEMT devices. The work was supported in part by US Army SMDC Contract Number W9113M-04-C-0048
References: 1. M.J.Manfra et. al. "High Quality AlGaN /GaN HEMTs Grown by MBE on Semi-Insulating Silicon Carbide" Presented at the MRS Meeting, Dec.2-6, 2002 (Boston), Published in MRS Proceedings on GaN (2003) 2. F.W.Clarke et. al." Gate Current and Analytical Modeling in Insulating Gate III-N Hetero-Structure Field Effect transistors" Presented at the MRS Meeting, Dec.2-6, 2002 (Boston), MRS Proceedings on GaN (2003) 3. Magnolia Optical Technologies Inc. Phase I Final report, Contract Number DASG60-02-P-0180 (November 2002). 4. Magnolia Optical Technologies, Inc. Phase II Program effort, Contract Number W9113M-04-C-0048.

FF13.13
Relations between passivation layer deposition conditions and AlGaN/GaN HFET performance. Pankaj B. Shah, Benjamin Huebschman, Ali Darwish, Nelson Y. Mark, Mike Derenge and Ken A. Jones; Sensors and Electron Devices Directorate, US Army Research Laboratory, Adelphi, Maryland.

AlGaN/GaN HFETs are being passivated with SiNx, SiO2, and other dielectrics and polymers with the goal of increased lifetime, power handling, and reliability. Results reported in the literature by some research organizations indicate that SiNx passivated devices have demonstrated the best performance among which are mitigated gate lag effects, reduced DC/RF dispersion, and increased gain, PAE and breakdown voltage. However, different research organizations have different techniques for depositing the passivation layer and the stoichiometry and other characteristics are expected to be different. More significantly, the passivation layer used is usually one that had been optimized for another material system but directly transferred to AlGaN HFETs without analysis, such as a SiN layer that was originally developed for InP HFETs. We are investigating how variation in the deposition of passivation layers will directly affect the performance of AlGaN/GaN HFETs. Standard AlGaN/GaN HFETs were fabricated with e-beam evaporated ohmic contacts, an inductive coupled plasma reactive ion etched mesa isolation and gate recess, and e-beam evaporated Schottky contacts. Fabricated HFETS block up to 180 V. Then a PECVD oxide, nitride or oxynitride layer is deposited and etched in locations where overlay metals are deposited for wirebond contacts. Variation of the flow rates of SiH4, He, N2O, He, and N2, as well as variation in RF power, deposition temperature and pressure lead to different thickness and composition of the passivation layer. Steady state device performance is obtained from load pull and probe station I-V analysis. The HFET passivation layers are also compared with data from ellipsometer, reactive ion etch rate, and atomic force microscopy. Furthermore, for control of other process parameters, we analyze the ohmic contacts with transfer-length measurement, and the electronic properties of the material with Hall and capacitance-voltage measurements. Trends relating deposition condition to passivated AlGaN/GaN HFET performace are reported.

SESSION FF14: Poster Session: Contacts/Processing
Chairs: Juergen Christen and Tsvetanka Jeleva
Tuesday Evening, November 29, 2005
8:00 PM
Exhibition Hall D (Hynes)

FF14.1
Forming device quality oxide interfaces on GaN using remote plasma techniques. J. P. Long[1], Cristiano Krug[1], Marc Ulrich[2,1] and Gerald Lucovsky[1]; [1]Physics, North Carolina State University, Raleigh, North Carolina; [2]Physics, Army Research Office, Research Triangle Park, North Carolina.

GaN-based electronics and optoelectronics have been hindered by the lack of a reproducible high quality dielectric, i.e., one having an interface state density below 10^{11} cm^{-2}. This is due to the uncontrolled growth of a subcutaneous Ga_2O_3 layer during oxide deposition on GaN. This problem can be circumvented using remote plasma techniques to separately and independently control the interface oxide and deposited oxide; controlled formation of the Ga_2O_3 interface oxide prevents parasitic growth during deposition. Using this methodology, we have prepared SiO_2/Ga_2O_3/GaN oxide stacks. GaN substrates were prepared by wet chemical cleaning and in-situ remote plasma cleaning. 8 nm of Ga_2O_3 was formed by remote plasma assisted oxidation. This was followed by plasma assisted nitridation to provide a monolayer of nitrogen at the Ga_2O_3/GaN interface. SiO_2 was deposited by remote plasma enhanced chemical vapor deposition and annealed at 900°C by RTA. The defect density for this gate stack was measured to be 2-3 x 10^{11} cm^{-2}. This defect density is approaching device quality and theoretical studies indicate that the density can be lowered further by replacing the deposited SiO_2 with Al_2O_3 or HfO_2. Bond constraint theory states that the interface state density scales with the square of the difference in the average number of bonds per atom, Nav, in the two materials forming the interface.

The difference between Nav for SiO_2 and Ga_2O_3 is significant whereas they are similar for Al_2O_3, HfO_2 and Ga_2O_3. Further details of this theory will be presented as well as spectroscopic and electrical studies of oxides on Si and GaN to support this conclusion.

FF14.2
Comparative Study of the Interfacial Reaction of Thin Ti/Al/Mo/Au Ohmic Contacts to AlGaN/GaN Heterostructure and to n-GaN. Liang Wang[1,3], Fitih M. Mohammed[1,3] and Ilesanmi Adesida[2,3]; [1]Department of Materials Science and Engineering, University of Illinois at Urbana-Champaign, Urbana, Illinois; [2]Department of Electrical and Computer Engineering, University of Illinois at Urbana-Champaign, Urbana, Illinois; [3]Micro and Nanotechnology Laboratory, University of Illinois at Urbana-Champaign, Urbana, Illinois.

Ti/Al/Mo/Au multilayer metallization scheme has been demonstrated to have low ohmic contact resistivity, high thermal stability, and sharp edge acuity on n-GaN and AlGaN/GaN heterostructures. In this paper, we report a comparative study of the post-annealing interfacial reaction of thin Ti/Al/Mo/Au metallization on both AlGaN/GaN heterostructures and n-GaN materials by transmission electron microscopy (TEM), scanning TEM (STEM) and energy dispersive x-ray spectroscopy (EDS). In the case of AlGaN/GaN heterostructures, the reaction does not proceed uniformly. The threading dislocations originating at the interface between GaN and AlN buffer layer were revealed to serve as fast diffusion path for Ti and TiN islands were observed to form preferentially along the dislocations. These TiN islands penetrated through the AlGaN layers up to a depth of >130 nm. The TiN islands have a large total area of intimate contact with the two-dimensional electron gas, and since no tunneling of electron through the AlGaN is required, a low resistance ohmic contact is obtained. In the case of n-GaN, the reaction proceeded uniformly. A continuous interfacial TiN layer of 5-20 nm thick was observed to have formed. The TiN/metal interface is flat while the TiN/GaN interface is rough. In both cases, thin Au-Al segregations with a thickness of ~1-3 nm were detected at the TiN/GaN interface. Despite these metallurgical barrier layers, excellent ohmic contact performance were achieved. In addition, TiN formation is believed to be achieved by diffusion of Ti into the semiconductor followed by a thermal reaction with N.

FF14.3
Fabrication and electrical characteristics of Ti/Al ohmic contact to Si^+ implanted GaN. Nobuyuki Ito[1], Akira Suzuki[1], Mitsunori Kawamura[1], Kazuki Nomoto[1], Takeshi Kasai[2], Tomoyoshi Mishima[3], Taroh Inada[1], Tohru Nakamura[1] and Masataka Satoh[1]; [1]Department of EECE and Research Center of Ion Beam Technology, Hosei University, Koganei, Tokyo, Japan; [2]Chemitronics, Musashimurayama, Tokyo, Japan; [3]Hitachi Cable, Tsuchiura, Ibaraki, Japan.

GaN is of great interest for high-power, high-frequency electron devices. Ohmic contact plays an important role in these devices. The heavy doping in the contact layer is effective for the reduction of the contact resistance. Ion implantation is a useful technique to dope the impurity into the selected area in GaN. The application of ion implantation technique to the ohmic contact formation might realize the good ohmic contact on GaN with the low contact resistance. There are, however, few reports on the ohmic contact to implanted GaN. In this study, we investigated the electrical properties of Ti/Al ohmic contact formed on Si^+ implanted GaN. The sample used in this study was undoped GaN with a thickness of 2 microns, grown on the sapphire substrate. Si ions were implanted at the energy of 150keV and doses of 5 x 10^{13} and 5 x 10^{14} /cm^2, which would dope Si impurity at the concentration of 1.0 x 10^{18} and 1.0 x 10^{19} /cm^3 at the surface, respectively. The implanted samples capped by Si-nitride layer with a thickness of 50 nm were annealed at 1200 ^{o}C for 2 min in N_2 gas flow. In the Si^+ implanted GaN annealed at 1200 ^{o}C, the sheet carrier concentration was estimated to be 3.9 x 10^{13} and 4.2 x 10^{14} for the dose of 5 x 10^{13} and 5 x 10^{14} /cm^2, respectively, which corresponds to about 80 % electrical activity of the implanted Si. The ohmic contact to Si^+ implanted GaN was fabricated by annealing the deposited Ti/Al films at the temperature ranging from 600 to 800 ^{o}C for 3 min in Ar gas flow. The thickness of Ti and Al was 50 and 200 nm, respectively. The specific contact resistance (Rc) of the formed ohmic contact was evaluated by means of circular TLM method. In the Si^+ implanted GaN with a dose of 5 x 10^{13} /cm^2, Rc was evaluated to be 1.2 x 10^{-6}, 5.1 x 10^{-6}, and 6.4 x 10^{-6} ohm-cm^2 for the samples annealed at 600, 700, and 800 ^{o}C, respectively. The sheet resistance was also estimated to be about 2900 ohm/sq., which is consistent with the result of Van der Pauw measurement. In the case of the Si^+ implanted GaN with a dose of 5 x 10^{14} /cm^2, the value of Rc was 3.5 x 10^{-6} and 4.0 x 10^{-6} ohm-cm^2 for the samples annealed at 700 and 800 ^{o}C, respectively. However, the sample annealed at 600 ^{o}C revealed the extremely low Rc of 1.7 x 10^{-8} ohm-cm^2. The sheet resistance of 220 ohm/sq. was obtained. In the case of the annealing at 600 ^{o}C, Rc is remarkably reduced with the increase of carrier concentration at the surface through the ion implantation. On the other hand, the annealing above 700 ^{o}C results in the similar Rc ranging from 3 x 10^{-6} to 6 x 10^{-6} ohm-cm^2, which is correlated to the melt of Ti/Al layer during the annealing. In conclusion, we demonstrated that the heavy doping by the ion implantation is very useful to reduce the specific contact resistance for GaN/Ti/Al ohmic contact. The extremely low Rc of 2 x 10^{-8} ohm-cm^2 was achieved by the annealing at 600 ^{o}C for the Si^+ implantation with a dose of 5 x 10^{14} /cm^2.

FF14.4
TiB_2, CrB_2 and W_2B based High Thermal Stability Ohmic Contacts to n-GaN. Rohit Khanna[1], S. J. Pearton[1], C. J. Kao[2], I. Kravchenko[3], F. Ren[3], G. C. Chi[2], A. Dabiran[4] and A. Osinsky[4]; [1]Department of Materials Science and Engineering, University of Florida, Gainesville, 32611, Florida; [2]Department of Electrical Engineering, National Central University, Chung-Li, 32054, Taiwan; [3]Department of Chemical Engineering, University of Florida, Gainesville, 32611, Florida; [4]SVT Associates, Eden Prairie, 55344, Minnesota.

A novel metallization scheme for Ohmic contact (Ti/Al/X/Ti/Au) to n-GaN using different high temperature borides was studied using contact resistance, scanning electron microscopy and Auger Electron Spectroscopy measurements. X in the metallization scheme can be W_2B, TiB_2 or CrB_2. A minimum contact resistance of 7x10^{-6} Ω.cm^2 was achieved for W_2B based scheme at an annealing temperature of 800 ^{o}C. For TiB_2 it was of 2x10^{-6} Ω.cm^2 at 800°C and 900°C and 8x10^{-6} Ω.cm^2 for CrB_2 at 800°C. Contact resistances were found to be essentially independent of measurement temperature, indicating that tunneling plays a dominant role in the current transport. For W_2B, the outdiffusion of Ti to the surface at temperatures of ~500°C, and at 800°C the onset of intermixing of Al within the contact was found to occur. By 1000°C, the contact showed a reacted appearance and AES showed almost complete intermixing of the metallization. The reliability measurements for the contact resistance of W_2B based contact showed excellent stability for extended periods at 200°C and other metallization schemes, too, are promising candidates for operation in environment at around 350°C, which simulates the type of device operating temperature that might be expected for operation of GaN-based power electronic devices.

FF14.5
Anti-diffusion barriers for gold-based metallization to GaN. Anna Piotrowska[1], Eliana Kaminska[1], Pawel Jagodzinski[1], Marek Guziewicz[1], Artur Szczesny[1,2], Adam Barcz[1,3], Rafal Jakiela[1,5], Elzbieta Dynowska[3], Anna Stonert[4], Andrzej Turos[4,5], Stephan Figge[6], Roland Kroeger[6] and Detlef Hommel[6]; [1]Institute of Electron Technology, Warsaw, Poland; [2]Warsaw University of Technology, Warsaw, Poland; [3]Institute of Physics PAS, Warsaw, Poland; [4]Institute of Nuclear Problems, Warsaw, Poland; [5]Institute of Electronic Materials Technology, Warsaw, Poland; [6]University of Bremen, Bremen, Germany.

Great interest exists in GaN-based materials since the successful demonstration of optoelectronic and microelectronic devices. The formation of stable and reliable ohmic and Schottky contacts has been a problem in achieving good performance of those devices. This is especially true for p-type ohmic contacts for LDs where internal heating still limits their output power and lifetime, as well as for Schottky electrodes for high-power/high-frequency HEMTs. Au and Au-based alloys/multilayers remain the most commonly applied materials for metallization systems in III-V semiconductor device technology. These include making active contacts as well as metal overlayers for bonding and interconnection purposes. In particular, Pd(Ni)Au metallizations have been proven to give low resistivity ohmic contacts to p-GaN and high Schottky barriers on n-GaN, lacking however stability at elevated temperatures. The success and the ultimate shortcomings of Au-based metallizations are strongly related to thermally activated interfacial reactions in Au/III-V semiconductor system. These occur at relatively low temperatures and thus may have deleterious effect on the long-term stability of contact properties. In this work an approach has been undertaken to solve this problem by using anti-diffusion barrier layers. To be applicable, these thin-film materials must fulfil specific requirements of: high thermal stability, high electrical conductivity, high resistance to corrosion, and compatibility with technology of device structures. In search for effective anti-diffusion barrier, conducting amorphous films have been considered as the most promising ones. This is because, owing to the lack of grain boundaries, fast diffusion path are eliminated in such materials. In this respect, two material systems have been taken into consideration in this work and their most promising candidates worked out. These included conducting TM-nitrides, with Ta-Si-N, Ti-Si-N, and Ti-W-N, and conducting TM-oxides, with Ru-O and Ru-Si-O as representatives. Thin films of TM-nitrides and TM-oxides

have been deposited by magnetron sputtering in reactive plasma. The effect of sputter-deposition parameters on the electrical resistivity and microstructure of barrier layers have been investigated. Heat treatments have been carried out at temperatures up to 1000°C in N_2 and Ar flow. Electrical characterisation of metal/semiconductor contacts involved measurements of I-V characteristics and specific contact resistance. Interfacial reactions at metal/semiconductor interface were analysed by RBS, SIMS, XRD, and TEM. We show that by optimising parameters of the reactive sputtering thin-film conducting amorphous barriers can be obtained effectively suppressing the interaction between GaN and Au under annealing up to 900oC and protecting Au-based metallization from Au overlayer. Work supported by grants from EC G5RD-CT-2001-00566-DENIS and from the State Committee for Scientific Research 3 T11B 008 026.

FF14.6

Damage Recovery of Mg^{+}-implanted GaN During Rapid Thermal Annealing. Igor O Usov, Terry G Holesinger and Paul N Arendt; MST-STC, Los Alamos National Laboratory, Los Alamos, New Mexico.

Ion implantation is widely used for selective-area doping of various semiconductors. The main obstacle in application of this technique for fabrication of GaN-based devices is poor recovery of implantation-induced damage. This problem is of prime concern for GaN doping with acceptors, because defects tend to compensate and getter the implanted acceptors rendering them electrically inactive. Therefore, the understanding of processes taking place during annealing of ion implanted GaN is of key importance. In this work we present a study of the influence of implantation and annealing conditions on damage recovery in GaN epitaxial films implanted with 50 keV Mg^{+} ions. Ion implantation was performed at room temperature at doses of $5x10^{14}$ and $4x10^{15}$ cm^{-2}. Rapid thermal annealing was carried out in vacuum at 900 and 1000 ^{o}C for times ranging from 1 to 100 seconds. Rutherford backscattering/channeling spectrometry and transmission electron microscopy (TEM) were used to determine the amount of damage and microstructure of the implanted layers before and after annealing, respectively. No complete damage recovery was achieved. Annealing time dependence of implantation-induced damage recovery demonstrated a transient behavior. For both Mg^{+} ion doses and at both annealing temperatures a significant recovery took place during the first 5 seconds and almost vanished for longer annealing times. For high Mg^{+} ion dose ($4x10^{15}$ cm^{-2}), damage recovery was more efficient at the annealing temperature of 1000 ^{o}C compared to 900^{circ}C. But for low Mg^{+} ion dose ($5x10^{14}$ cm^{-2}) the amount of damage was almost independent of the annealing temperature. TEM results show that microstructure of as-implanted samples and its subsequent change upon annealing play important roles in the observed transient behavior.

FF14.7

Investigation of Plasma Etching Damage Effect on p-GaN with a New Ridge Type Test Structure. Taehoon Jang, Y.J. Sung, O.H. Nam and Y. Park; Photonics Program Team, Samsung Advanced Institute of Technology, Gyeonggi-Do, South Korea.

GaN based optoelectronic devices such as light emitting diode (LED) and laser diode (LD) have been widely developed. Among critical problems which degrade properties of LD, the plasma etching damage on the ridge sidewall would be one of the key factors on affecting performance of LD. Particularly for a ridge type LD, long ridge cavity in rectangular shape would have more chance to get damaged as it is etched by plasma. However, the effect of plasma etching damage on a ridge type sidewall has not been discussed in detail because of its difficulty in measurement and analysis. In this paper, we have developed a new structure which can measure plasma etching damage by measuring the breakdown voltage of Schottky diode on p-type GaN. Unlike conventional circular Schottky diode structures, our test structure has rectangular Schottky contact patterns in order to measure the exact effect of plasma etch damage on the sidewall of rectangular ridge shape. The test structure has six different width size (from 1.5 to 4.0 um) with 600 um length rectangular Schottky contact and isolated with three different rectangular trench width (6, 10 and 20 um). The exposed bottom surface of trench would affect the breakdown voltage as well. Thus the effects of Schottky contact width and trench width versus different plasma etching conditions would be correlated with plasma etching damage. Also the breakdown voltage measurements on 15 different ohmic contact pads with rectangular Schottky contact would reveal the etch damage within specific region from the top Schottky contact. This will show the uniformity of etch damage on Schottky contact. Understanding of the plasma etching damage regarding the etching condition in a rectangular shape Schottky diode is essential to improve electrical properties of LD. Results based on breakdown voltage will explain the plasma etch damage effect and suggest the optimal plasma etching condition in ridge type laser diode.

FF14.8

Investigation of dry etch damage and recovery on GaN.
Youn Joon Sung, Teahoon Jang, Joong-Kon Son, Ok-Hyun Nam and Yongjo Park; Photonics Progam Team, Samsung Advanced Institute of Technology, Suwon, South Korea.

Dry etching technique is an effective method for GaN-based device fabrication such as LEDs and laser diodes. However, dry etching process usually induces damage on the GaN surface and makes degradation on the optical and electrical properties of the GaN-based device. Therefore it is important to study the dry etch-induced damage effects on the device properties. In this study, we investigated the effects of etch-induced damage using current-voltage (I-V) characteristics and the reverse breakdown voltages on GaN-based laser diodes. To evaluate the amount of etch damage from the dry etched GaN surface, the power dependent photoluminescence (PL) spectra were examined. The PL results showed that the dry etch damage on GaN surface can propagate about 60nm from the surface. Wet etching technique using NaOH and KOH solution was used to remove the dry etch damage on the GaN surface. The results showed that the reverse breakdown voltage on the wet etched sample change from -3V to -10V.

FF14.9

Substrate influence on the high-temperature annealing behavior of GaN: Si vs. sapphire. David Pastor[1], Ramon Cusco[1], Luis Artus[1], Enrique Iborra[2], Juan Jimenez[3], Francisca Peiro[4], German Gonzalez[5] and Enrique Calleja[6]; [1]Inst. Jaume Almera, C.S.I.C., Barcelona, Spain; [2]Tecnologia Electronica, ETSIT, Univ.Politecnica Madrid, Madrid, Spain; [3]Fisica Materia Condensada, Univ. Valladolid, Valladolid, Spain; [4]Electronica, Univ. Barcelona, Barcelona, Spain; [5]Fisica Aplicada III, Univ. Complutense, Madrid, Spain; [6]ISOM and Ingenieria Electronica, ETSIT,Univ.Politecnica Madrid, Madrid, Spain.

The use of Si(111) substrates for the growth of high-quality GaN layers is an interesting alternative for optoelectronic applications due to the low cost of these substrates and the possibility of integration with existing Si technology. However, the poor thermal stability of Si substrates may cause problems in the growth of GaN/Si layers by metalorganic techniques, which often use high growth temperatures, as well as in annealing processes required to remove lattice damage originated by ion implantations. We have studied the effects of rapid thermal annealing (RTA) at 1300°C on GaN epilayers grown on AlN buffered Si(111) and on sapphire substrates. An AlN capping layer was deposited on all the epilayers to prevent surface decomposition. The samples were characterized by scanning electron microscopy (SEM), energy dispersive x-ray microanalysis (EDX), optical confocal microscopy (OCM), focused ion beam (FIB) etching, cathodoluminescence (CL) and Raman spectroscopy (RS). After RTA, the GaN epilayers grown on Si display a stained surface which was not observed in GaN epilayers grown on sapphire. SEM and OCM images taken on the epilayers grown on Si revealed the presence on the sample surface of crater-shaped inhomogeneities that develop around protruding nuclei of typically 50 mm diameter. EDX element analysis yields a high concentration of Si in the crater regions as well as non-stoichiometric concentrations of Ga and N, with an excess of N. RS measurements were performed inside and outside the crater regions using a Raman confocal microprobe. Whereas in the homogeneous regions the characteristic Raman spectrum of GaN was obtained, no Raman peaks of GaN were observed in the spectra of the crater regions, which displayed only a broadened Si peak and several peaks corresponding to crystalline Si3N4. These results suggest that a substantial migration of Si from the substrate to the surface takes place during the high-temperature RTA, which severely alters the material in the crater regions. CL measurements confirm the existence of two different emission regions in the annealed sample. SEM images obtained during a FIB etching performed in one of the craters showed in real time the coalescence of Ga droplets forming a pool of liquid Ga at the bottom of the etched region. The degradation of the GaN epilyer was much less severe for RTA at 1100 °C. In contrast, the same RTA process carried out on a GaN epilayer grown on sapphire did not produce such a dramatic alteration of the material. Analysis by SEM and OCM revealed a uniform surface and RS confirmed that the GaN layer maintained its homogeneity and crystallinity after RTA. The different annealing behavior of GaN grown on Si(111) constitutes a severe drawback for a widespread use of such substrates in integrated device processing that require high-temperature annealing treatments.

FF14.10

Maskless Surface-Charge Lithography for GaN Micro- and Nanostructuring. Ion Tiginyanu[1,2], Veaceslav Popa[2] and Olesea Volciuc[2]; [1]Institute of Applied Physics, Academy of Sciences of Moldova, Chisinau, Moldova; [2]National Center for Materials Study and Testing, Technical University of Moldova, Chisinau, Moldova.

We developed a novel maskless lithography for GaN micro- and nanostructuring, the so called surface charge lithography. Low-energy

Ar ion beam treatment was used to induce on the semiconductor surface a layer of trapped negative charge shielding the material against photoelectrochemical etching. The surface charge was designed and exploited as lithographic mask for the purpose of cost-effective manufacturing of GaN mesa- and nanostructures using photoelectrochemical etching in aqueous solution of KOH. We demonstrated the possibility to induce the surface negative charge by mechanical means, e.g., using needles, microscribers and nanotips, see Applied Physics Letters, Vol. 86, 174102 (2005). The surface charge lithography was implemented at the Technical University of Moldova for the purpose of manufacturing selective gas sensors and high frequency Schottky diodes based on gallium nitride layers grown by metalorganic chemical vapor deposition. The ability to generate high resolution patterns of trapped negative charge can, in principle, be exploited for a variety of micro- and nanofabrication purposes. In particular, we demonstrate the feasibility of the proposed technology for manufacturing high-quality GaN nanowalls and nanocolumns. The technological approach involved was highly appreciated at the U.S. Largest Invention Tradeshow held in Pittsburgh, PA on June 8-11, 2005, the authors winning a Gold Medal.

FF14.11
Etch-back technique for the planarization of the various crystal orientations of GaN. Adrian Williams and Theodore Moustakas; Electrical and Computer Engineering, Boston University, Boston, Massachusetts.

The planarization of GaN is a topic with sparse representation in the literature. Currently there are a few groups that report chemo-mechanical methods to planarize GaN of nitrogen polarity, but gallium polar material remains a challenge due to its extreme resistance to chemical attack. To date, we have not seen literature addressing the successful global planarization of gallium polar material, nor the other remaining crystal orientations. With the inevitable commercialization of GaN substrates, methods must be developed to planarize them prior to their use as substrates for the epitaxial growth of devices. In this work we demonstrate the etch-back technique, utilizing inductively couple plasma (ICP) etching, to be a robust planarization method for the various crystal orientations of GaN. Rough GaN films grown on sapphire by the HVPE method with rms surface roughness of 100-300nm have been planarized to sub-nanometer levels irrespective of the crystal orientation as evidenced from atomic force microscopy measurements (AFM) of planarized c-plane (both Ga and N polar films), a-plane, and m-plane GaN films. In addition, similar results have been obtained for very rough freestanding GaN through the use of lapping followed by the etch-back procedure. In order to achieve these results, the spin deposition of various Clariant brand photoresists was investigated to determine conditions that achieve the highest degree of planarity of the sacrificial layer when deposited onto surfaces of varying degrees of roughness. Additionally, ICP etching conditions have been identified to match the etch rates of GaN with photoresist to maximize process efficiency.

FF14.12
3-Nitride Light Emitting Diodes with Transparent Nanoparticle-Embedded p-Ohmic Electrodes. June-O Song[1], Hun Kang[2], David Nicol[3], Ian T. Ferguson[4], Hyun-Gi Hong[5] and Tae-Yeon Seong[6]; [1]Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, Georgia; [2]Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, Georgia; [3]Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, Georgia; [4]Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, Georgia; [5]Materials Science and Engineering, Gwangju Institute of Science and Technology, Gwangju, South Korea; [6]Materials Science and Engineering, Korea University, Seoul, South Korea.

GaN-based semiconductors have recently attracted much attention for their various applications as high-brightness light emitting diodes (LEDs) in the short-wavelength regions. Even though these GaN-based LEDs are very successful, poor ohmic contact at electrode/p-type GaN interface is still a problem that led to LEDs with limited performance. In order to achieve high performance GaN-based LEDs, it is necessary to reduce specific contact resistance, enhance optical transmittance, and improve reliability of p-contact layer. In this work, we report on low resistance and highly transparent ohmic contacts to p-type GaN, which employed various transparent nanoparticles between p-type GaN and transparent conducting electrode. Differently from the reported ohmic schemes such as ITO and Ni(O)/ITO, our ohmic schemes developed by the introduction of transparent nanoparticles have shown many advantageous characteristics for 3-nitride LEDs. It is shown that the specific contact resistances of $\sim 10^{-4}$ Ωcm^2 obtained for our developed ohmic structures, when the samples are annealed in air ambient. It is further shown that for the annealed samples, their optical transmittances at a wavelength below 460 nm are superior to the annealed Ni/Au and Ni/ITO. To understand detailed ohmic formation mechanisms, electronic transport mechanisms and interfacial reactions are described and discussed by means of current-voltage (I-V), Auger electron spectroscopy, and x-ray photoelectron spectroscopy. Furthermore, light emitting diodes (LEDs) are fabricated using developed ohmic schemes. The typical I-V characteristics of the LEDs with transparent nanoparticle-embedded p-ohmic layers exhibit a forward-bias voltage of within 4.0 V at injection current of 20 mA, which is comparable to that of the LEDs with the annealed Ni/Au and Ni/ITO. The output power of the LEDs is also characterised and discussed.

SESSION FF15: Electronic Devices II
Chair: Thomas E. Kazior
Wednesday Morning, November 30, 2005
Grand Ballroom (Sheraton)

8:00 AM FF15.1
III-Nitride Epitaxial Material on Large-Diameter Semi-Insulating SiC Substrates for High Power RF Transistors. Adam W. Saxler[1], Ed Hutchins[1], Austin Blew[2], Yifeng Wu[3], R. Peter Smith[1], Scott Sheppard[1], Sten Heikman[3], Primit Parikh[3] and Scott Allen[1]; [1]Cree, Inc., Durham, North Carolina; [2]Lehighton Electronics, Inc., Lehighton, Pennsylvania; [3]Cree Santa Barbara Technology Center, Goleta, California.

Metalorganic chemical vapor deposition (MOCVD) was utilized for the formation of uniform III-Nitride layers on silicon carbide substrates up to 100mm in diameter. Room temperature mobilities over 2000 cm^2/Vs are routinely obtained using AlN interlayer structures. Sheet resistivity and mobility uniformity values of $<1\%$ have been demonstrated for AlGaN/AlN/GaN high electron mobility transistor (HEMT) structures on 100 mm diameter, on-axis, Si-face, high-purity semi-insulating 4H-SiC substrates. Recent materials and device results will be presented.

8:15 AM FF15.2
Digital Dielectric Deposition for Metal-Oxide-Semiconductor AlGaN/GaN HFETs. Shiva Rai, Naveen Tipirneni, Rongming Chu, Alexei Nickolaevich Koudymov, Vinod Adivarahan, Grigory Simin, Yang Jinwei and Asif Khan; Electrial Engineering, University of South Carolina, Columbia, South Carolina.

AlGaN/GaN based heterojunction field-effect transistors (HFETs) with their demonstrated superior power performance at microwave frequencies are attractive for RF applications. However, their microwave output powers degrade under high bias/high RF load mainly because of an increase in the gate leakage currents. In contrast, AlGaN/GaN Metal-Oxide-Semiconductor HFETs (MOSHFETs) are stable because of their inherent low gate leakage currents. The PECVD (plasma enhanced chemical vapor deposition) SiO2 layers are commonly used as the gate insulators. However the PECVD SiO2 films, even as thin as 150-200Å, increase the threshold voltages by as much as 3-5 volts as compared to the Schottky gate HFETs. Simply reducing the insulator thickness to tune the threshold voltage invariably degrades the oxide quality. This results in increased gate leakage currents and premature gate breakdown. Our present study includes two new approaches to avoid this problem while yielding low threshold MOSHFETs. In this paper we first describe a new pulsed atomic layer (PAL) deposition technique that allows for a precise thickness control and significantly improves the quality of SiO2 layers even as thin as 80Å. In contrast to the conventional PECVD process, in PAL pulses of silane (SiH4) and nitrous oxide (N2O) are alternately supplied to the growth chamber. The SiO2 layer thickness and hence the threshold voltage can thus simply be controlled by the number of precursor pulses. In addition, the PAL process yields better structural quality due to the 2-dimensional nature of the growth. MOSHFETs with PAL deposited SiO2 layers with the thickness ranging from 80Å to 160Å have been fabricated and tested. For the thinnest SiO2 layer the MOSHFET threshold voltage was only 1 V higher than that for the HFET. The gate leakage currents of all the MOSHFET device types were at least 3 orders lower than the HFET. MOSHFETs with PAL deposited SiO2 dielectrics showed no threshold voltage dispersion in the pulsed I-V characteristics. Field-plated MOSHFETs demonstrated the RF powers of 12 - 15 W/mm at 2 GHz with stable RF operation over 100 hours at 3 dB RF power compression. Low-threshold MOSHFETs were also fabricated using ZrO2 as the gate dielectric. Compared to SiO2, ZrO2 has the advantage of combining the high dielectric constant (25) and the large energy bandgap (7.8eV) simultaneously. The MOSHFETs with 17 nm thick ZrO2 film under the gate have the threshold voltage which is only 0.5V higher than that of the HFETs fabricated on the same wafer and the gate leakage current that is 4-5 orders of magnitude less. Field-plated ZrO2 based MOSHFETs yielded the RF performance similar to the low-threshold SiO2 based devices. The RF

power density was 14 W/mm at 2 GHz CW operation. The RF power instability was within 0.3 db during 72 hours stressing. In the paper details of oxide deposition, its quality analysis and the impact on the MOSHFET properties will be discussed in detail.

8:30 AM FF15.3
Normally Off-Mode AlGaN/GaN HFET with p-Type Gate Contact. Norio Tsuyukuchi, K. Nagamatsu, Y. Hirose, M. Iwaya, S. Kamiyama, H. Amano and I. Akasaki; Materials Science and Engineering, Faculty of Science and Technology, 21st COE Program Nano-factory, Meijo University, Nagoya, Japan.

The power density of Si-based power devices is approaching the material limits of Si. GaN-based group III nitride semiconductors are one of the most promising materials for high-voltage, high-power and high-speed devices, because the breakdown field of GaN is about ten times larger than that of Si. GaN-based electron devices have received much attention for a variety of high-power electronics applications. However, most of these devices have been fabricated as depletion mode (normally on-mode) devices to date. In order to achieve low-power consumption circuits, normally off-mode devices are essential. The p-n junction induces high built-in potential which causes full depletion of the device channels at zero gate bias. Hu et al. [1] fabricated an AlGaN/GaN HFET by selectively growing a p-n junction gate which shows non-negligible leakage current at zero gate bias. In this study, we fabricate normally off- mode AlGaN/GaN HFET with a p-GaN gate contact which shows extremely low drain current at zero gate bias. HFET was grown on a sapphire (0001) substrate by metal organic vapor phase epitaxy. The device consists of a low-temperature buffer layer, a 2-μm-thick unintentionally doped GaN, a 15-nm-thick unintentionally doped $Al_{0.07}Ga_{0.93}N$ layer, and a 7-nm-thick Mg-doped GaN layer. After the activation of Mg acceptors, mesa isolation was performed using Cl_2/Ar plasma in reactive ion etching (RIE). Next, a Ni/Au ohmic contact was deposited as a gate contact on the p-GaN; then another area of p-GaN was etched by RIE. After that, source and drain contacts for AlGaN were fabricated by Ti/Al/Ti/Au. The devices had a gate length of 2 μm, a gate width of 100 μm, and a distance between the drain and the source of 8 μm. The device is in the normally off-mode with a threshold voltage of 0.05 V. Leakage current density as low as 18.2 nA/mm was achieved when the gate was biased at 0 V and a drain was biased at 20 V. Details of the device performance will be discussed. Acknowledgement This work is partially supported by the MEXT (Contract 5206003) and Akasaki Research Center, Nagoya University. Reference [1] X. Hu, G. Simin, J. Yang, M. Asif Khan, R.Gaska, M. S. Shur, Elec. Lett., 36 (2000) 753.

8:45 AM FF15.4
Flip Chip Mounting for Improved Thermal Management of AlGaN/GaN HFETs. Hangfeng Ji[1], Andrei Sarua[1], Martin Kuball[1], Jo Das[2], Wouter Ruythooren[2], Marianne Germain[2] and Gustaaf Borghs[2]; [1]Physics Department, University of Bristol, Bristol, United Kingdom; [2]IMEC, Leuven, Belgium.

AlGaN/GaN HFETs are very promising for high power applications. The reliability particularly in relationship with thermal management for integrated devices remains an important concern, since high current densities arise in the HFET during device operation. Good thermal management of the HFETs is essential in order to obtain an appropriate device lifetime. We report on a temperature study of flip-chip mounted multi-finger AlGaN/GaN HFETs. Flip-chip mounting can be used to improve thermal device management, in particular for devices grown on lower thermal conductivity substrates such as sapphire. In this study, we compare designs having different flip-chip layouts. Both temperature measurements and 3D temperature simulations will be presented. To measure the device temperature micro-Raman spectroscopy is used. This technique has a high spatial resolution of $<1\mu$m, required due to the small device openings in current AlGaN/GaN HFETs. The HFETs were grown on double-side polished sapphire substrates, which allowed us to measure the temperature through the substrate of the flip-chip mounted devices. In this way the GaN-temperature could be measured, not only between the source-drain-gate contacts, but also directly underneath them, which is a major advantage. In one particular flip-chip design, the peak temperature next to the gate reached 205°C when the device was operated at 1.5W. Temperature maps around the location of flip chip bumps showed a clear temperature minimum of about $\triangle$T=10-20°C in their vicinity, illustrating their vital role for heat extraction. The experimental results are in good agreement with 3D thermal modelling. The results show that minimizing the distance between the bumps and the active area of the HFET is essential for obtaining a low device operating temperature. This is an important conclusion towards future "System in a Package" designs that include AlGaN/GaN HFETs.

9:00 AM FF15.5
III-Nitride Metal-Oxide-Semiconductor-Heterostructure Voltage Controlled Capacitor. Zijiang Yang, Alexei Koudymov, Vinod Adivarahan, Grigory Simin, Jinwei Yang and M. Asif Khan; Electrical Engineering, University of South Carolina, Columbia, South Carolina.

Over the past ten years significant progress has been made in III-Nitride based high-power electronics components. A key to this progress is the fabrication of AlGaN/GaN heterostructure field-effect transistors (HFETs) with record rf-powers. As the III-Nitride technology matures, there is an excellent potential for fabricating functional elements resulting from it that can be monolithically integrated into various high-power high-temperature circuits and systems. In this paper, we propose and demonstrate a novel high power voltage controlled capacitor (VCC) based on III-Nitride Metal-Oxide-Semiconductor-Heterostructure (MOSH), such as SiO_2/AlGaN/GaN or SiO_2/AlGaN/InGaN/GaN. One plate of the MOSH capacitor is formed by the metal electrode deposited on top of the SiO_2 layer. A low-resistive 2D electron gas (2DEG) channel at the AlGaN/GaN hetero-interface serves as the other conducting plate. When a negative voltage is applied to the metal plate exceeding the threshold value, the 2D electron gas channel depletes and the MOSH capacitor drops down. In principle the MOSH capacitor acts somewhat similar to a MEMS capacitor; however, being an all solid-state device it has several key advantages. Experimental MOSH capacitors were fabricated over nominally undoped AlGaN/GaN heterojunction grown on SiC substrates. The dielectric layer was obtained by depositing $\sim$100$\AA$ layer of SiO_2 using Plasma Enhanced Chemical Vapor Deposition (PECVD) system. The sheet resistance measured using on-wafer RF mapping system, was $R_{SH} \approx 320$ ohm. The ON-state MOSH capacitance is around 3.5 nF/mm^2 for a 200 $\AA$ thick AlGaN barrier layer. The OFF-state fringing capacitance is around 0.2 pF per millimeter of the contact perimeter. The cut-off frequency in ON state (limited by the transmission line effects) depends on the device area to perimeter ratio, and can be as high as several GHz. Below the cut-off frequency, the MOSH ON/OFF ratio exceeds 100:1. At higher frequencies the ON-state capacitance is reduced by transmission line effects however the ON/OFF ratio of around 20:1 with a Q-factor exceeding 100 can be easily reached at 1 GHz. The high-frequency Q factor of a MOSH capacitor is around 30-50% higher than that of identical geometry Schottky- based device (without a dielectric layer). In addition the MOSH capacitor has a very high power handling capabilities, the exact power limits being depended on a particular circuit. When used as an RF switch, the maximum switching power as high as 60 W/mm was measured, in a close agreement with the simulation results. For the similar Schottky-based capacitor, the maximum power is at least 4 times lower. Thus our novel MOSH based voltage controlled capacitor is a promising building block for high power RF switching, phase shifters, parametric amplifiers and other functional rf-elements.

9:15 AM FF15.6
Effect of Fe Doping in i-Layer and Passivation Scheme on Performance Characteristics of GaN $p-i-n$ Rectifiers. Jae Limb, Dongwon Yoo, Jae-Hyun Ryou and Russell Dupuis; School of Electrical and Computer Engineering, Geogia Institute of Technology, Atlanta, Georgia.

GaN-based $p-i-n$ rectifier structures were grown on 6H-SiC substrates by metalorganic chemical vapor deposition. The structure consists of 0.1μm p-GaN, 2.5μm i-GaN, 2.5μm n-GaN, and AlN buffer layer on the substrates. p- and n-layers were doped with Mg and Si to have $\sim$1X10^{18} and $\sim$5X10^{18} cm^{-3} hole and electron free carrier concentration, respectively. i-layer was doped with Fe, which is known as deep acceptor in GaN, intended for compensation of low n-type background doping for the GaN:nid layer using Cp_2Fe precursor from 0 to 1x10^{16} cm^{-3} dose. Fabrication of rectifier devices was carried out by employing mesa definition by etching down to n-GaN:Si layer using Cl_2/He ICP etching and n- and p-ohmic contacts by Ti/Al/Ti/Au and Pd/Au metallization scheme, respectively. Various passivation schemes were employed in the structure such as SiO_2 Si_1N_{1-x}, and epitaxially re-grown GaN:Fe. Major performance characteristics of the rectifier, such as on-state resistance, breakdown voltage, and reverse bias leakage current, are compared depending on Fe doping level in i-layer and passivation scheme. Under optimized condition $\sim$500V of reverse bias breakdown and less than 3 mΩcm^2 of on-resistance were achieved.

SESSION FF16: Contacts to HEMTS
Chair: Thomas E. Kazior
Wednesday Morning, November 30, 2005
Grand Ballroom (Sheraton)

9:30 AM FF16.1
Low Temperature Selected Area Re-Growth of Ohmic Contacts for III-N FETs. Yoganand Nrusimha Saripalli[1], Chang Zeng[2], Joseph P. Long[3], Judith Grenko[1], Mark Johnson[1] and Doug

Barlage[2]; [1]Materials Science and Engineering, North Carolina State University, Raleigh, North Carolina; [2]Dept of Electrical and Computer Engineering, North Carolina State University, Raleigh, North Carolina; [3]Dept of Physics, North Carolina State University, Raleigh, North Carolina.

GaN has a wide band gap energy, higher electron mobility, high saturation velocity, and excellent thermal properties making it a promising material for high power and high frequency electronic devices. The development of enhancement mode GaN metal oxide semiconductor (MOS) transistors has been elusive due to the non-availability of a good insulating gate dielectric and the difficulty in forming of ohmic source/drain regions. Ion-implantation of dopants causes severe lattice damage requiring a high temperature post-implant anneal and has not been a successful method to obtain acceptable low-resistance source/drain regions. At the same time, gate dielectrics for most compound semiconductors, in addition to difficulties in minimizing the density of interface states which pin the Fermi level by inducing trap levels in the midgap, are degraded by instabilities as a result of high temperature annealing. The paper presents the development of ohmic source/drain contacts for GaN MOSFETs by selected area epitaxial regrowth. Re-growth of GaN on patterned substrates by metal-organic chemical vapor deposition (MOCVD) employs a growth regime to decrease the enhanced growth rates and island formation that result from the diffusion of precursors to the selected area. The enhanced growth rate is 4.5um/hr compared to 0.5um/hr of the as-grown GaN on the unpatterned substrate. The enhanced growth rate also results in heavily porous GaN. Selected area growth, device processing, the material and device characterization results will be presented. In particular the selected area growth of doped contacts in the 800C temperature range leads to superior morphology and contact resistance as compared to similar contacts grown at 1060C. The contact resistivity of the n+ re-growth region measured was ~2x10-4 ohm-m and the morphology of the re-grown region was comparable to the as-grown GaN with an RMS roughness ~2nm. The success of fabricating low temperature contacts for GaN enhancement mode MOS transistors is a critical step in fabricating these devices opening new applications.

9:45 AM FF16.2
Evidence for Non-Interfacial-Nitride Formation Ohmic Contact Mechanism in Silicon Containing Ti/Al/Mo/Au Metallization for AlGaN/GaN HEMTs. Fitih M. Mohammed[1,2], Liang Wang[1,2] and Ilesanmi Adesida[1,3]; [1]Micro and Nanotechnology Laboratory, University of Illinois at Urbana-Champaign, Urbana, Illinois; [2]Materials Science and Engineering, University of Illinois at Urbana-Champaign, Urbana, Illinois; [3]Electrical and Computer Engineering, University of Illinois at Urbana-Champaign, Urbana, Illinois.

The high breakdown voltage and high saturation current of AlGaN/GaN HEMTs present great potential for applications in power and microwave amplification. To this end, numerous metallizations, mostly Ti/Al-based, have been utilized to obtain reduced contact resistance. We report the formation of excellent ohmic contacts to AlGaN/GaN heterostructures by the incorporation of Silicon in Ti/Al/Mo/Au metallization. Contact resistance and specific contact resistivity as low as 0.12 Ω-mm and $3.8\text{x}10^{-7}$ Ω-cm^2, respectively, have been obtained for Ti (15 nm/Si(15 nm)/Al(60 nm)/Si(15 nm)/Mo(35 nm)/Au(50 nm) contact scheme annealed at 850 ^{o}C for 30 s. TEM analyses have revealed that the ohmic contact formation mechanism in these metallizations is dependent on competing reaction pathways between interfacial-nitride and silicide formation, the later dominating in silicon-rich schemes. A direct correlation between Si content and ohmic performance is observed. The results obtained reveal non-nitride interfacial reaction products, mainly Al-Au-Si intermetallics, formation and penetration to the AlGaN/GaN interface where the 2DEG is located. Correlation between electrical properties and microstructure of silicon containing Ti/Al/Mo/Au contact metallizations will be discussed, and ways of optimization of contact properties will be presented.

SESSION FF17: Electrical/Transport Properties
Chair: Tom Myers
Wednesday Morning, November 30, 2005
Grand Ballroom (Sheraton)

10:15 AM FF17.1
Nanoscale capacitance-voltage measurements on AlGaN/GaN heterostructures. Goutam Koley[1], L. Lakshmanan[1], N. Tipirneni[1], M. Gaevski[1], A. Khan[1], Ho-Young Cha[2] and M. G. Spencer[2]; [1]Electrical Engineering, University of South Carolina, Columbia, South Carolina; [2]Electrical Engineering, Cornell University, Ithaca, New York.

A simple and novel technique for quantitative nanoscale capacitance-voltage (C-V) measurements has been developed and used to characterize the two dimensional electron gas (2DEG) at the interface of AlGaN/GaN heterostructures. Good correlations were obtained between the threshold voltage and 2DEG as measured by the nanoscale and the large area C-V measurements performed on these samples. The measurement technique is sensitive enough to indicate change in 2DEG confinement and density at the AlGaN/GaN interface as the dc voltage swept from low to high negative bias and vice-versa. For AlGaN/GaN heterostructures grown on sapphire substrates by various techniques such as, novel migration enhanced metal-organic chemical vapor deposition (MEMOCVD) as well as normal MOCVD, the 2DEG density and confinement were generally found to increase after low to high negative bias sweep. We attribute this to a reduction in the surface trapped negative charge caused by the negative bias sweep. For nanoscale C-V measurements under UV illumination, the threshold voltage increased significantly indicating an increase in the 2DEG density, however, no significant change in the 2DEG confinement was observed as before, since the trapped electrons at the surface were nullified by the photogenerated holes. The capacitance signal magnitude was found to be dependent on the measurement frequency as well as the characteristics of the cable. It is expected that with proper optimizations, measurement resolution of a few aF can be obtained, which will allow direct quantitative C-V measurements using probe tips with diameter of a few tens of nm.

10:30 AM FF17.2
Weak Antilocalization in Polarization-Doped AlGaN/GaN Heterostructures. N. Thillosen, V. A. Guzenko, Th. Schaepers, N. Kaluza and H. Hardtdegen; Institute of Thin Films and Interfaces ISG1, Research Center Juelich, Juelich, NRW, Germany.

The properties of AlGaN/GaN heterostructures have been a subject of great activity because of their application in high frequency, high power, and high temperature devices. Magnetotransport measurements give the possibility to study the properties of a two-dimensional electron gas. Indeed, Shubnikov-de Haas oscillations of a two-dimensional electron gas can be observed at high magnetic fields. Moreover, magnetoresistance measurements close to zero magnetic field give the possibility to investigate the weak localization and weak antilocalization arising from AlGaN/GaN heterostructures. The latter is related to the spin-orbit interaction on the spin of the carriers present in these heterostructures and is a key-feature of the spin-transistor proposed by Datta and Das [1]. As a matter of fact, the spin orientation between the electrodes of this novel device should be manipulated by the controllable strength of the spin-orbit interaction in the two-dimensional electron gas. In order to obtain information on spin-orbit effects in AlGaN/GaN heterostructures we therefore analyzed the weak antilocalization observed in the magnetoresistance. Polarization-doped AlGaN/GaN heterostructures were grown by metalorganic vapor phase epitaxy (MOVPE) on the (0001) surface of sapphire substrates. First a 3 μm-thick GaN buffer layer was grown, followed by a $Al_{0.3}Ga_{0.7}N$ layer with a thickness of 20 nm. Magnetotransport measurements were performed over a magnetic field range from -50 mT to +50 mT at various temperatures between 0.1 and 18 K. The Hall-bars were prepared by optical lithography and Ar^+-ion-beam-etching technique. The metals used for the ohmic contacts were Ti/Al/Ni/Au. The mobility and carrier concentration in the single occupied subband were obtained from the Shubnikov-de Haas oscillations with the respective values of 9100 cm^2/Vs and 6.2×10^{12} cm^{-2}. In our case, the Shubnikov-de Haas oscillations of the two-dimensional electron gas reveal the occupation of a single subband in the nearly triangular quantum well. At low magnetic field, weak localization as well as weak antilocalization were observed, showing that strong spin-orbit interaction is present in our structures. A previous report [2] explained the weak-antilocalization as being related to the intersubband scattering due to the occupation of a second subband in a modulation-doped quantum well. We show that weak antilocalization is also present in a polarization-doped quantum well with a single subband being occupied. In this perspective, temperature-dependent weak antilocalization measurements will be presented and analyzed using adequate theoretical models. Finally, the relevant scattering times like elastic scattering time, dephasing time as well as spin-orbit scattering time have been extracted. [1] S. Datta and B. Das, Appl. Phys. Lett. Vol. 56, pp. 665-667, 1990. [2] J. Lu et al., Appl. Phys. Lett., Vol. 85, pp. 3125-3127, 2004

10:45 AM FF17.3
Improvement in *p*-type AlGaN activation process with a Ni catalytic layer. Takayuki Naono[1], Hiroshi Fujioka[2,3], Jun Okabayashi[1], Masaharu Oshima[1] and Hisayuki Miki[4]; [1]Department of Applied Chemistry, The University of Tokyo, Tokyo, Japan; [2]Institute of Industrial Science, The University of Tokyo, Tokyo, Japan; [3]Kanagawa Academy of Science and Technology, Kanagawa, Japan; [4]Showa Denko K.K., Chiba, Japan.

Although *p*-type doping of AlGaN is inherently important to fabricate

ultraviolet light-emitting diodes and laser diodes, it is well known that the activation of Mg in AlGaN is quite difficult. One of the reasons for this stems from difficulty in the removal of hydrogen atoms in AlGaN which passivate the Mg acceptors. We have recently found that thin Ni films deposited on Mg doped GaN strongly enhance the desoption of hydrogen from the surfaces catalytically.[1] In this study, we report that the Ni catalytic layer technique is quite useful to achieve high carrier concentrations at low annealing temperatures for p-type AlGaN. Samples used in this study were 500 nm thick Mg-doped $Al_xGa_{1-x}N$ (x=0.03 and 0.08) grown on sapphire (0001) substrates by metalorganic chemical vapor deposition (MOCVD) with non-doped GaN buffer layers. The Al fractions of the films were determined with X-ray diffraction. Mg concentration in AlGaN layers was estimated to be 7.0×10^{19} cm^{-3} by SIMS. Ni films with a nominal thickness of 10 nm were deposited on the sample surfaces, followed by annealing at various temperatures in N_2 ambient with a conventional furnace for p-type activation. Change in the hydrogen concentration was measured by SIMS and a gas desorption from the sample surfaces was studied by thermal desorption spectroscopy (TDS). Electrical properties of the films were investigated by the Hall measurements with the van der Pauw geometry. Samples annealed with the Ni catalytic layers showed higher hole concentrations than those annealed without the Ni layers for all the annealing temperatures. It should be also noted that the use of Ni catalytic layer reduces the threshold temperature where activation starts. The highest hole concentrations, which were obtained by annealing at as low as 700 °C with Ni layers, were 8.3×10^{16} cm^{-3} and 8.0×10^{16} cm^{-3} for $Al_{0.03}Ga_{0.97}N$ and $Al_{0.08}Ga_{0.92}N$, respectively. SIMS measurements have revealed that hydrogen concentration in AlGaN annealed with Ni were much lower than those annealed without Ni. This result indicates that the Ni films strongly enhance desorption of hydrogen atoms from AlGaN, which is the key process for activation of p-type AlGaN. A H_2 TDS spectrum from $Al_{0.10}Ga_{0.90}N$ with the Ni layer showed a large desorption peak at 450 °C, while no remarkable peaks were observed for the sample annealed without the Ni layer. This large desorption peak is quite consistent with the threshold temperature where activation starts. These results indicate that the Ni catalytic layer technique is quite useful to achieve high carrier concentrations at low annealing temperatures for p-type AlGaN. Reference [1] I.Waki *etal.*, Appl. Phys. Lett. **78** (2000) 2899.

11:00 AM FF17.4
Polarization Induced 3-Dimensional Electron Slabs in Graded AlGaN Layers. John Simon[1], Siddharth Rajan[2], Kejia Wang[1], Huili Xing[1] and Debdeep Jena[1]; [1]Electrical Engineering, University of Notre Dame, Notre Dame, Indiana; [2]ECE, University of California, Santa Barbara, California.

III-V nitrides exhibit large polarization fields in their crystal structure. It is possible to use these fields to engineer novel doping methods and devices. By using polarization fields, regions of mobile charge can be induced. Carriers can be produced without the need of introducing any dopants into the lattice. A good understanding of the transport properties of these carriers is required for new device applications. Transport studies were performed over various graded AlGaN layers grown by MOCVD. Samples were linearly graded from GaN to $Al_{0.3}Ga_{0.7}N$ over different thicknesses. Agreement in sheet carrier density is seen between both Hall and Capacitance-Voltage measurements. Room temperature Hall densities and mobilities were determined to be 9x10^{12}cm^{-2} and 860cm^2/Vs respectively. Temperature dependent Hall measurements were performed on all samples inside a closed-cycle refrigerator. Temperature was varied from 10K to 300K. A small (~10%) decrease in sheet carrier density is observed in all samples with increasing temperature over the tested temperature range. No carrier freeze out is observed at lower temperatures, which bodes well for devices that undergo large temperature variations. The small decrease in charge is attributed to a change in polarization with changing temperature. Temperature-dependent capacitance-voltage measurements were also performed on a temperature controlled chuck. The temperature was varied from -60°C to 200°C and the apparent carrier profile was extracted. The sheet carrier density calculated from the carrier profile appears to have the same dependence with temperature as seen in Hall measurements. Volume carrier density is seen to decrease with increasing graded layer thickness. This gives two degrees of freedom in obtaining the desired doping level. This bodes well for device design. Material composition and/or layer thickness can be changed independently to generate a desired level of doping. Widely tunable 3-dimensional electron slabs of different 3D electron densities and slab widths can thus be created by this technique. Electron impurity scattering is minimized in all samples due to the lack of intentional impurities in the lattice. Electron mobility is dominated by alloy scattering in the graded AlGaN layer. This gives rise to higher mobilities of carriers compared to impurity-doped 3-dimensional slabs of the same density. New devices can be achieved by using polarization induced doping, in which the absence of impurities can improve device performance. The technique of doping demonstrated offers a novel and attractive route to doping of high-Al composition AlGaN layers that are important in UV-light emitting Devices and HBTs.

11:15 AM FF17.5
Electron scattering due to V_{Ga}-O_N threading edge dislocations in n-type epitaxial wurtzite GaN. Jeong Ho You, Jun-Qiang Lu and H. T. Johnson; Department of Mechanical & Industrial Engineering, University of Illinois at Urbana-Champaign, Urbana, Illinois.

Threading edge dislocation lines in epitaxial wurtzite(WZ) GaN act as electron acceptor sites, thereby reducing free carrier concentration, electron mobility, and even bandgap luminescence. In the present work, the effect of electrically active V_{Ga}-O_N threading edge dislocations on drift and Hall mobility in n-type epitaxial WZ GaN is investigated theoretically. The charge distribution along the dislocation core is first obtained by means of a density functional theory atomistic calculation; the two N atoms near the missing Ga atom at the dislocation core are found to be electron acceptors. An accurate analytical expression for dislocation electrostatic strength is then derived for the case of up to -2q charge per structural unit of the threading dislocation core. This strength factor is determined by minimizing the total increase of free energy per site of the partially charged dislocation line. Two different models of scattering potentials for charged dislocation lines are then used to determine the dislocation effect on in-plane electron mobility, and closed form solutions for the dislocation contribution to drift and Hall mobility are derived for the more accurate potential. By estimating the effects of other scattering mechanisms, the total mobility is then compared with available experimental data. It is found that for free carrier concentrations higher than 10^{16}cm^{-3}, reducing dislocation density below 10^8cm^{-2} has little beneficial effect on total mobility for typical WZ GaN samples.

11:30 AM FF17.6
Highly p-Type a-GaN Grown on r-Plane Sapphire Substrate. Yosuke Tsuchiya, Y. Okadome, H. Furukawa, A. Honshio, M. Iwaya, S. Kamiyama, H. Amano and I. Akasaki; Materials Science and Engineering, Faculty of Science and Technology, 21st-Century COE Program "Nano-Factory", Meijo University, Nagoya, Japan.

C-plane nitride-based short-wavelength light-emitting diodes (LEDs) have been commercialized and widely used all over the world. Its strong internal polarization field perpendicular to the interface of the quantum well causes spatial separation of electrons and holes in the quantum well and leads to the reduced transition probability, thus limiting the performance of these LEDs. Several groups have studied the growth of nonpolar a-plane GaN (a-GaN) on r-plane sapphire substrates. The performance of the LEDs on r-plane sapphire is still inferior to LEDs grown on c-plane sapphire substrates. In addition to the poor crystallinity, the lower hole concentration of less than 7×10^{17} cm^{-3} [1] in p-type a-GaN poses serious problems in realizing high-performance LEDs. The growth of high-quality a-GaN is essential for achieving highly p-type a-GaN. In this study, Mg-doped a-GaN films have been grown on r-plane sapphire substrates by metalorganic vapor phase epitaxy. The a-GaN layer was grown on a 0.5°-off r-plane sapphire substrate. [2] After thermal cleaning of the r-plane sapphire substrate surface in a hydrogen atmosphere at approximately 1150°C, it was cooled to 1100°C at which an a-AlN layer about 200 nm thick, an a-AlGaN layer about 700 nm and a-GaN layer about 2.0 μm were grown. This stacked structure leads to high-crystallinity a-GaN with root mean square surface roughness of around 1.1 nm and full width half maximum of X-ray rocking curve of around 1000 arcsecs. Then, 1.5-μm-thick Mg-doped a-plane GaN layers with different Mg concentrations were grown. Hole concentration was found to increase with increasing amount of Mg-source gas. The highest hole concentration thus achieved was 2×10^{18} cm^{-3}, hole mobility was 4.5 cm^2/Vs and resistivity was 0.7 ohm·cm. The activation energy of Mg acceptors was found to be 150 meV by the temperature-dependent Hall-effect measurement. [1] A. Chakraborty, H. Xing, M. D. Craven, S. Keller, T. Mates, J. S. Speck, S. P. DenBaars, and U. K. Mishra: J. Appl. Phys. 96 (2004) 4494 [2] A. Honshio, Y. Miyake, H. Kasugai, T. Kawashima, K. Iida, M. Tsuda, M. Iwaya, S. Kamiyama, H. Amano, and I. Akasaki: Ext. Abstr. (65th Autumn Meet 2004); Japan Society of Applied Physics and Related Societies, 2a-W-2.

SESSION FF18/EE9: Joint Session: Zinc Oxide Materials and Devices Including Alloys II
Wednesday Afternoon, November 30, 2005
Grand Ballroom (Sheraton)

1:30 PM *FF18.1/EE9.1
ZnCdO/ZnMgO and ZnO/AlGaN Heterostructures for UV and Visible Light Emitters. Andrei V Osinsky[1], J. W. Dong[1], J. Q. Xie[1], B. Hertog[1], A. M. Dabiran[1], P. P. Chow[1], S. J. Pearton[2], D. C. Look[4], W. Schoenfeld[3], O. Lopatiuk[3], L. Chernyak[3] and M.

Gerhold[5]; [1]SVT Associates, Eden Prairie, Minnesota; [2]University of Florida, Gainesville, Florida; [3]University of Central Florida, Orlando, Florida; [4]Wright State University, Dayton, Ohio; [5]U.S. Army Research Office, Durham, North Carolina.

In this presentation properties of hybride ZnO/GaN and all-ZnO based heterostructures based on the results of modeling are presented. Novel band-gap engineering of type-II/type-I hexagonal heterostructures incorporating the strong piezoelectric and spontaneous polarization fields in ZnMgO and AlGaN-based materials was investigated. Band structures of various MgZnO/AlGaN/GaN heterojunctions were simulated, revealing a strong hole confinement near n-ZnO/p-AlGaN interface with a hole sheet density up to 1.8x10Î3 cm-2. The formation of hole accumulation layer and triangular well near the hybride heterointerface can increase the probability of radiative recombination under forward bias. The simulation results for electrical and optical emission characteristics of hybride n-ZnO/p-AlGaN heterostructures with specific emphasis on creating efficient LEDs are presented. Crystallographic, optical, and electrical properties confirm that high quality MgZnO and ZnCdO layers grown epitaxially on both GaN/Sapphire templates and ZnO substrates using RF-plasma enhanced MBE. A summary of the characterization results of CdxZn1-xO layers with Cd mole fraction up to x=0.78 including high resolution X-ray diffraction, SIMS, RBS, optical transmission, photoluminescence, and cathodoluminescence mapping is presented. Dependence of the fundamental optical band gap on the composition of CdxZn1-xO alloys is reported. Band gap bowing and the possible effect of composition micro-fluctuation in ternary CdxZn1-xO alloys on the optical bandgap is also discussed. Strong optical emission observed at RT throughout the visible spectrum from CdxZn1-xO layers with various compositions demonstrates a great potential for use as a light emitter. Finally we present results of demonstration of UV-blue ZnO-based LEDs.

2:00 PM FF18.2/EE9.2

New Wide Band Gap Alloy BeZnO Growth. Yungryel Ryu[1], Jorge A. Lubguban[2], A. B. Corman[2], Henry W. White[2], J. H. Leem[3], M. S. Han[3], Y. J. Youn[4] and W. J. Kim[5]; [1]MOXtronics, Inc, Columbia, Missouri; [2]Physics Department, University of Missouri, Columbia, Missouri; [3]Moxtronix, Gwangju, South Korea; [4]Semiconductor Physics Research Center, Jeonbuk National University, Jeonju, South Korea; [5]Department of Physics, Changwon National University, Changwon, South Korea.

We have synthesized a new wide band gap oxide alloy, BeZnO. The BeZnO films have been deposited on sapphire substrates by our hybrid beam deposition growth method. The value of energy band gap of BeZnO can be efficiently engineered to vary from the ZnO band gap (3.3 eV) to that of BeO (10.6 eV). BeZnO can be used for fabricating films and heterostructures of ZnO-based electronic and photonic devices and for other applications. The properties of BeZnO will be presented in this talk.

2:15 PM FF18.3/EE9.3

Optically Tunable MgZnO Nanocrystallites and their Structural Properties. John L. Morrison[1], Xiang-Bai Chen[1], Jesse Huso[1], Heather Hoeck[1], James Mitchell[1], Dario A. Machleidt[1], Leah Bergman[1] and Tsvetanka Zheleva[2]; [1]Physics Department, University of Idaho, Moscow, Idaho; [2]Army Research Lab, Adelphi, Maryland.

ZnO and MgZnO are promising emerging materials capable of luminescence in the ultraviolet (UV) spectral range. ZnO exhibits hexagonal wurtzite crystal structure and has a bandgap of 3.37 eV while MgO has the rock-salt cubic structure and a bandgap of 7.5 eV. Thus the MgZnO alloy system may provide a new optically tunable family of wide bandgap materials usable in UV luminescent applications as well as a potential conjugate material in AlGaN-MgZnO hybrid devices. MgZnO nanocrystallites with an average size of $\sim$ 30 nm were synthesized via thermal decomposition. Samples having Mg concentrations of 0%, 7%, 13%, 26% were studied via photoluminescence, resonant-Raman scattering, TEM, XRD, and XPS. The TEM and XRD studies indicated that at these concentrations the crystallites still retain the hexagonal Wurtzite structure. The nanocrystallites found to exhibit room-temperature UV- photoluminescence for which the peak position depends on the Mg concentration: a blueshift of $\sim$ 0.3 eV was achieved as the Mg concentration increases from zero up to 26 percents. Our observed shift is somewhat smaller than that reported for MgZnO thin films with a similar Mg concentration; this could be attributed to the crystallites' surface defects, which result from the large surface to volume ratio inherent to crystals at the nano-scale. Our resonant Raman studies of the first and second order LO modes exhibited a shift of up to 30 wavenumbers as the Mg concentration increased from 0 to 26%; this result is consistent with those reported for the E1(LO) mode of MgZnO thin film alloys. Additionally, studies of the temperature response of the MgZnO nanocrystallites over a range of 77-900 K will be presented and issues such as anharmonic interaction, photoluminescence thermal shift, and crystalline stability at these temperatures will be discussed. Leah Bergman gratefully acknowledges NSF CAREER DMR-0238845 and DOE-DE-FG02-04ER46142, as well as the American Chemical Society PRF 40749-AC10.

3:30 PM FF18.4/EE9.4

Piezoelectric characterization and stimulated emissions of ZnO pillars within hexagonal arrays. Robert Hauschild[1], Hongjin Fan[2], Woo Lee[2], Marin Alexe[2], Armin Dadgar[3], Alois Krost[3], Kornelius Nielsch[2], Margit Zacharias[2] and Heinz Kalt[1]; [1]Institut of Applied Physics, University of Karlsruhe, Karlsruhe, Germany; [2]Max Planck Institute of Microstructure Physics, Halle, Germany; [3]Institute of Experimental Physics, Otto-von-Guericke University, Magdeburg, Germany.

ZnO pillars with diameter in the submicron range promise lower threshold laser action due to a higher Q-factor of the resonator and a larger overlap of the guide modes with the gain medium. We applied a template-assisted approach to spatially separated and hexagonally-arranged ZnO pillars which are typically 300 nm in diameter and 1.5 μm in height. The piezoelectric properties of single pillars are characterized using piezoresponse force microscopy (PFM). The obtained piezoelectric coefficient d33 is (7.5$\pm$0.6) pm/V, which is to our knowledge, the first reported value for a single pillar. This value is much smaller than the reported value of ZnO nanobelts but comparable to that of bulk ZnO. The bulk like piezoelectric behavior indicates that the pillars have low density of structural defects. The optical properties are studied using micro-photoluminescence (PL) spectroscopy which allows both cw and time-resolved measurements. The luminescence of the sample is bright up to room temperature, uniform and scale independent. The pillars show intense excitonic emissions and phonon replica at temperatures above 100 K. The formation of phonon replica peaks in the PL spectrum together with the low defect-related emission and the bulk like decay time of 200 ps reflects the high crystalline quality of the nanopillars. With increasing the pump power, a new sharp peak due to exciton-exciton scattering emerges accompanied by an evident threshold behavior, which is a sign of stimulated emissions of the pillars. The stimulated emission from a single pillar will be presented in detail. Based on the PFM and micro-PL results, the quality of our ZnO pillars meets the requirement for their potential applications like actuators and optoelectronic switch.

3:45 PM FF18.5/EE9.5

UV Lasing in Three-Dimensional, Optically Active ZnO Photonic Crystals Fabricated by Atomic Layer Deposition. Michael Georg Scharrer[1], Alexey Yamilov[2], Xiaohua Wu[2], Larry Aagesen[1], Hui Cao[2] and Robert P. H. Chang[1]; [1]Materials Science & Engineering, Northwestern University, Evanston, Illinois; [2]Physics and Astronomy, Northwestern University, Evanston, Illinois.

Atomic layer deposition is a versatile growth technique that allows surface-controlled, layer-by-layer deposition of highly conformal films on substrates with complex geometries. We have fabricated ZnO inverse opals by infiltrating carboxylate-modified polystyrene opal templates using a low-temperature ALD process. The resulting structures have high filling fractions, possess both first- and higher-order photonic band gaps in the near-UV to visible spectrum, and exhibit efficient photoluminescence. ZnO acts as both the dielectric and source material in these optically active three-dimensional photonic crystals, and we can utilize the photonic band structure to modify the emission properties. We have observed suppression and redistribution of the spontaneous emission due to both first-order and higher-order band gaps. We also report mirrorless, tunable, and highly directional photonic crystal lasing in the near-UV spectrum when the band gaps overlap the gain spectrum of ZnO. We correlate our experimental results to calculated band structures, taking into account the frequency-dependent dielectric function of ZnO near the absorption edge.

4:00 PM FF18.6/EE9.6

Low-Temperature Plasma-Assisted MOCVD Growth of ZnO. Maria Losurdo[1], Pio Capezzuto[2], Giovanni Bruno[1], Graziella Malandrino[3], Manuela Blandino[3] and Ignazio Fragala[3]; [1]Chemistry, IMIP-CNR, Bari, Italy; [2]Chemistry, University of Bari, Bari, Italy; [3]Chemistry, University of Catania, Catania, Italy.

ZnO is a wide band gap (Eg = 3.37 eV) semiconductor material that recently has attracted much interest due to its high photocatalytic activity, and its potential applications in optoelectronic devices, such as short- wavelength lasers and light-emitting diodes due to its strong excitonic feature and lasing properties even at room temperature. ZnO nanostructures have also numerous applications in such diverse areas as piezoelectric transducers, phosphors, sensors and transparent

conducting films. In the past decade, most of research has been focused on the growth of ZnO thin films by techniques such as sputtering, spray pyrolysis, sol-gel, electron-beam deposition. However, the importance of MOCVD for the growth of ZnO should be re-considered, as this technique has enabled the commercial application of GaN and related materials. Therein, we present and discuss the growth process and structural and optical properties of ZnO thin films and nanostructures grown by MOCVD also plasma-assisted (PA-MOCVD) using oxygen plasma excited by 13.56MHz rf-power. A new precursor Zn(TTA)2-tmed (HTTA=2-thenoyltrifluoroacetone,TMED=N,N,N,N-tetramethylethylendiamine) is used. Different substrates, including Si(100), 4H- and 6H-SiC(0001) and sapphire (0001), are used for nanostructured films, since their different surface tension is used for inducing different ZnO nanoparticles size and distribution. These substrates are also treated in situ using various plasmas (Ar-, H2, O2,) in order to change the ZnO nanoparticles nucleation and investigate their impact on material properties. The impact of substrate temperature ranging from 300C to 600C and of plasma parameters (r.f. power, O2 partial pressure and N2 addition) on ZnO thin films is presented for both MOCVD and PA-MOCVD. In situ real time monitoring of the growth process is carried out using laser reflectance interferometry (LRI). X-ray diffraction (XRD) is used for investigation of deposition parameters on the structure. The surface morphologies of ZnO films is examined by atomic force microscopy (AFM). The electrical properties are studied using the 4-probe Hall measurements and electrical force microscopy. Spectroscopic ellipsometric (SE) spectra of the dielectric function acquired from 0.75 to 6.5 eV are used for investigating the optical properties (exciton of ZnO appears in dielectric function) as a function of film structure. Optical properties are also investigated by photoluminescence to establish correlation between film structure and optical efficiency. XRD measurement showed that the quality of ZnO film grown at lower temperature around 300 C with optimized RF power is better than that of the film grown at higher temperature due to large thermal mismatch between ZnO and substrates. The results show plasma-assisted MOCVD is useful for ZnO growth of thin films and nanostructure at low temperature, being a key process for deposition of high quality ZnO films on various substrates.

4:15 PM FF18.7/EE9.7

Metal Organic Chemical Vapor Deposition of Zinc Oxide.
William E. Fenwick[1], Ming Pan[2,1], June-O Song[1], Nola Li[1], Shalini Gupta[1], Hun Kang[1], Ali Asghar[1], Martin Strassburg[1,3], Nikolaus Dietz[3] and Ian T. Ferguson[1,4]; [1]Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, Georgia; [2]Cermet Inc., Atlanta, Georgia; [3]Department of Physics and Astronomy, Georgia State University, Atlanta, Georgia; [4]School of Materials Science and Engineering, Georgia Institute of Technology, Atlanta, Georgia.

Zinc oxide (ZnO) is a material that shows great promise in optoelectronic applications because of its high exciton binding energy of ~60meV. Its bandgap of ~3.37eV potentially makes it an important material in the field of UV light emitters and detectors. However, such devices require that high quality undoped, n-type, and p-type ZnO films be grown. In this work, undoped ZnO thin films have been deposited on c-plane sapphire substrates and their structural, electrical, and optical properties have been investigated as part of a comprehensive study of the factors affecting ZnO thin film growth by metal organic chemical vapor deposition (MOCVD). A highly-modified vertical injection MOCVD system was used for the thin film growth, using diethyl zinc (DEZn) and various oxygen precursors. Growth temperature was varied from 300C to 680C, and growth pressures ranging from 10 Torr to 60 Torr were investigated. Disk rotation speed was varied from 600rpm to 1200rpm. VI/II ratios ranging from 56 to 900 were also investigated, as were different precursor flow rates. Optimal ZnO growth conditions were determined by a systematic variation of the growth parameters mentioned above in order to obtain reproducible, high-quality undoped, n-type, and p-type ZnO. At a growth temperature of 500C and a pressure of 50 Torr, the as-grown films show a growth rate of around 1mum/hr. Crystal quality was investigated using XRD, which showed asymmetrical ZnO peaks in omega-2theta, suggesting the formation of second phases or incorporation of excess Zn into the crystal. Preliminary investigations suggest that annealing the as-grown ZnO films at high temperatures increases the crystal quality as observed using X-ray diffraction (XRD). Surface morphology of the films was investigated using Atomic Force Microscopy (AFM). AFM revealed a surface roughness of between 18A and 40A for the as-grown films. Hall Effect measurements of the as-grown samples characterized them as n-type with carrier concentrations on the order of 1016 - 1017cm-3, most likely due to point defects. Photoluminescence (PL) was used to investigate the optical properties of the ZnO films. Room temperature PL data revealed a dominant near bandgap emission at 376nm. Furthermore, a broad luminescence band is observed between 400 and 500nm, and a luminescence band peaking at 504nm has also been observed. A more detailed study of these bands is provided by temperature-dependent PL investigations. The binding energy of the dopants and defect centers will be determined and used to identify the nature of the sub-bandgap states. The doping incorporation and carrier concentration will be studied by Raman spectroscopy. The crystalline quality of the thin films, and the presence of local vibrational modes due to dopants or point defects will be derived by such studies in order to optimize the growth process to grow reproducible, high-quality ZnO thin films.

4:30 PM FF18.8/EE9.8

Challenges in the Growth and P-type Doping of ZnO by Molecular Beam Epitaxy.
Tim Murphy, Jun Yang, Pallab Bhattacharya and Jamie Phillips; EECS, The University of Michigan, Ann Arbor, Michigan.

Zinc oxide and related oxide semiconductor alloys are emerging as important materials for active electronic and optoelectronic devices due to their desirable growth parameters, availability of native ZnO substrates, excellent optical properties, and near lattice-matched alloy system. High quality ZnO materials have been achieved using molecular beam epitaxy (MBE) with a plasma source to provide atomic oxygen. However, many challenges remain with respect to the repeatable growth of high quality material, and the ability to achieve reliable p-type doping. In this work, the growth of ZnO on c-plane sapphire by plasma assisted molecular beam epitaxy will be presented. Sapphire surface preparation plays a major role in determining the quality of epitaxial growth and the crystalline polarity of the wurtzitic structure, drawing parallels to GaN growth on sapphire. The oxygen environment for ZnO growth poses special challenges for the MBE growth technique, where oxygen resistant filament components and effusion cells resistant to oxidation at the source aperture are required. However, the oxygen ambient relaxes the requirements on vacuum purity required for MBE growth. Our experience with the unique aspects of ZnO growth over the course of more than 100 growths will be discussed. The crystalline, electronic, and optical properties of ZnO/Al_2O_3 will be presented and related to nucleation and growth conditions. X-ray diffraction measurements indicate epitaxial growth of the materials with rocking curve full width at half maximum ranging from 100 arcsec to more than 3600 arcsec. Electronic properties are found to generally correlate with x-ray diffraction measurements, where higher structural quality show carrier concentration and electron mobility in the range of 10^{17}-10^{18} cm^{-3} and 50 cm^2/Vs, respectively. In situ doping studies of ZnO using group V elements of nitrogen and arsenic will be presented in the goal of achieving reliable p-type ZnO. The electronic properties of nitrogen and arsenic doped ZnO will be presented. P-type behavior was observed on selected samples, where numerous samples showed n-type behavior despite large dopant concentrations. Challenges associated with the achievement of stable p-type behavior will be discussed.

4:45 PM FF18.9/EE9.9

High-quality *p*-type ZnO films with solid-source phosphorus-doping by molecular beam epitaxy.
Faxian Xiu[1], Zheng Yang[1], Leelaprasanna J. Mandalapu[1], Dengtao Zhao[1], Jianlin Liu[1] and Ward P. Beyermann[2]; [1]Department of Electrical Engineering, University of California, Riverside, Riverside, California; [2]Department of Physics, University of California, Riverside, Riverside, California.

ZnO materials have received much attention due to its tremendous potentials in UV optoelectronics and spintronics. Towards these applications, *p*-type ZnO with high carrier concentrations, reasonable mobilities and low resistivities is necessary. So far elements such as N, P, and As, as well as group III and group V co-doping have been used for producing *p*-type conductivities. In this presentation, we report high quality *p*-type ZnO films on *R*-plane sapphire by using a GaP effusion cell with a molecular beam epitaxy (MBE) system. A special design of Ga-trapping-cap system, including a dome-shaped and a disk-shaped pyrolytic-boron-nitride (PBN) extension cap on top of the PBN crucible, was employed to trap the parasitic Ga atoms, therefore providing a pure P_2 beam as the *p*-type dopants during the growth. Phosphorus-doped ZnO films of about 500nm were grown at 720^oC. The X-Ray Diffraction (XRD) spectra and the reflection high-energy electron diffraction (RHEED) patterns show that single crystalline ZnO films were grown on *R*-plane sapphire substrates. Room-temperature Hall and resistivity measurements show that the phosphorus-doped ZnO films with different GaP effusion cell temperatures are *p*-type and of low resistivity. One of the phosphorus-doped ZnO sample grown at the GaP effusion temperature of 750^oC exhibits a high hole concentration of $6.5\times10^{18}cm^{-3}$, high mobility of 8~10 cm^2/Vs and low resistivity of 0.6 Ω-cm. Temperature-dependent hole mobility measurements show phonon scattering dominant mechanism at higher temperature and Columbic effect dominant mechanism at lower temperatures. Photoluminescence (PL) measurements reveal a dominant acceptor-bound exciton (A^oX) emission at 3.317 eV at 8 K. The acceptor energy level of the phosphorus dopant is estimated to be 0.18 eV above the valence band, which is also consistent with the results of

the temperature-dependent PL measurements. A preliminary discussion of doping mechanism suggests that a phosphorus atom substitutes a Zn atom and creates two Zn vacancies simultaneously. This study suggests that GaP effusion cell is a good phosphorus dopant source for *p*-type ZnO MBE growth.

SESSION FF19: Visible LED + LD
Chair: Martin Kuball
Thursday Morning, December 1, 2005
Grand Ballroom (Sheraton)

8:00 AM *FF19.1
Advances in epitaxial growth and packaging for high-power InGaN-based light-emitting diodes. Andrew Y Kim, Farid Ahmed, Jerome Bhat, Eugene Chen, Lou Cook, Wendy Fan, Werner Goetz, Sebnem Karakoc, Reena Khare, Steve Maranowski, Tal Margalith, Paul Martin, Mira Misra, Yu-Chen Shen, Dan Steigerwald, Frank Steranka, Steve Stockman, Sudhir Subramanya and John Uebbing; Lumileds Lighting, US, LLC, San Jose, California.

Continuing development in InGaN-based high-power light-emitting diodes adds value to existing indicator and signage applications and enables never before possible applications in displays and illumination. While precise requirements vary by application, the key goals are to generate maximum flux per package with high wall-plug efficiency, excellent reliability, and flexible packaging and optics. Lumileds Lighting develops materials and device technologies that enable robust LEDs capable of operating at up to 5W input power per package with high wall-plug efficiency throughout the visible wavelength range and in white with a variety of color temperatures. Advances in epitaxial growth technology deliver improvements in internal quantum efficiency and light extraction efficiency and there is continuing work to understand and improve operating voltage. In synergy, flip-chip devices incorporating a reflective Ag-based reflector have been developed that offer light and heat extraction benefits and enable conformal phosphor-coated white LEDs with superior CCT uniformity. High-power packaging continues to be advanced to ensure reliable and efficient operation at over 1W. The overall result is a line of reliable Luxeon high-power LEDs that operate at wall-plug efficiencies matching or rivaling the state-of-the-art for conventional small signal LEDs and enable new applications such as LCD television, pocket projectors, and cell-phone camera flash in just the past year. In this presentation, examples of InGaN epitaxial growth and device engineering will be discussed and several new applications will be demonstrated.

8:30 AM FF19.2
A semipolar (10-1-3) InGaN/GaN green light emitting diode. Rajat Sharma[1], P. Morgan Pattison[1], Troy J. Baker[1,3], Benjamin A. Haskell[1,3], Robert M. Farrell[2], Hisashi Masui[1], Feng Wu[1,3], Steven P. DenBaars[1,2,3], James S. Speck[1,3] and Shuji Nakamura[1,2,3]; [1]Materials, University of California, Santa Barbara, Santa Barbara, California; [2]Electrical and Computer Engineering, University of California, Santa Barbara, Santa Barbara, California; [3]NICP/ERATO JST, UCSB Group, University of California, Santa Barbara, Santa Barbara, California.

The performance of conventional c-plane GaN-based optoelectronic devices suffers from the effects of strong polarization-induced electric fields along the conduction direction, which result in a reduced overlap between electron and hole wavefunctions. These devices consequently demonstrate low radiative recombination rates, and a blue-shift in peak emission wavelength with increasing bias. There have been several recent demonstrations of light emitting diodes (LEDs) fabricated on non-polar a- and m-plane GaN that show greatly reduced to zero blue-shift of peak emission wavelength, and other recent work on non-polar GaN has yielded hole concentrations that are almost an order of magnitude higher than for c-plane GaN. The effects of the strong polarization-induced electric fields may, conceivably, also be mitigated or potentially eliminated by growing films on so-called semipolar planes. A semipolar plane is any plane that may not be classified as a c-, a- or m- plane, and has at least two non-zero h, i, or k Miller indices and a nonzero l Miller index ({10-11}, {10-12} and {10-13} planes, for example). It is expected that devices grown on these semipolar planes should also demonstrate a reduced blue-shift in peak emission wavelength and higher hole concentrations. Further, recent work also suggests that the indium incorporation efficiency for growth on semipolar planes is comparable to that for growth on the c-plane. We demonstrate the first green InGaN/GaN LED grown on a planar semipolar (10-1-3) GaN template. The LED structure is grown by metalorganic chemical vapor deposition (MOCVD), and the 20 micron-thick, specular and optically transparent template is grown by hydride vapor phase epitaxy (HVPE). The fabricated devices have a peak emission wavelength of ~525 nm and demonstrate rectifying behavior, with a low turn-on voltage of 3.2 V. We observe a small ~7 nm blue-shift in the peak emission wavelength during electroluminescence measurements, over the range 20 to 250 mA. We also see an almost linear increase in the output power from 5 mA to 200 mA, with no appreciable decrease in the external quantum efficiency over the same range. We also observe evidence of polarization anisotropy in the emission from the semipolar green LEDs.

8:45 AM FF19.3
Charge Profiling of near-UV, Blue, Green GaInN/GaN Light Emitting Diode Structures. Yong Xia[1,2], Ya Ou[1,2], Ibrahim Yilmaz[1,2], Mingwei Zhu[1,2], Yufeng Li[1,2], Wei Zhao[1,2], Theeradetch Detchprohm[1,2], E. Fred Shubert[1,3] and Christian Wetzel[1,2]; [1]Future Chips Constellation, Rensselaer Polytechnic Institute, Troy, New York; [2]Department of Physics, Applied Physics and Astronomy, Rensselaer Polytechnic Institute, Troy, New York; [3]Department of Electrical, Computer, and Systems Engineering, Rensselaer Polytechnic Institute, Troy, New York.

Characterization of operational GaInN/GaN heterostructure devices is of primary relevance to their performance optimization and time-to-failure analysis. Typically, device performance data needs to be corroborated with structural information such as charge profiles of a pn-junction device. Non-destructive testing by capacitance-voltage profiling has been well established in many semiconductor systems, yet there is little documented application in AlGaInN heterostructures such as GaInN/GaN light emitting diodes (LEDs). Electric pulse and probe spectroscopy in time domain of forward biased LEDs has been applied by the Sandia group.[1] Here we demonstrate the usefulness of capacitance-voltage profiling operating conditions ranging from forward current injection to reverse-biased deep depletion of LED-type devices emitting in the spectral range of $420 - 540$ nm. Recently we succeeded in resolving individual quantum wells in GaInN/GaN active layers.[2] We now expand our approach to full structure analysis of such devices. Within a large set of samples with different layer thicknesses we observe and identify the step-wise depletion of individual quantum wells, barriers, and carrier injection layers. We directly determine thicknesses of most layers and their respective ionizable dopant concentrations. We find very close correlation with the designed structure and the layer thickness measured by x-ray diffraction analysis of the corresponding epiwafer. By means of this successful analysis we now have the opportunity to monitor epi process performance and stability as well as device degradation progress quasi-continuously over the device lifetime in a non-destructive mode. This will be of key relevance to further LED device optimization – particularly for the green (525 nm) and deep green (555 nm) spectral ranges. [1] R. J. Kaplar, S. R. Kurtz, D. D. Koleske, A. A. Allerman, A. J. Fischer, and M. H. Crawford, Mater. Res. Soc. Symp. Proc. Vol. 831 E10.9.1 (Materials Research Society, Warrendale PA, 2005) [2] Y. Xia, E. Williams, Y. Park, I. Yilmaz, J.M. Shah, E.F. Schubert, and C. Wetzel, Mater. Res. Soc. Symp. Proc. Vol. 831 E3.38 (Materials Research Society, Warrendale PA, 2005)

9:00 AM FF19.4
Direct Wafer Bonding of GaN and ZnO for Optoelectronic Application. Akihiko Murai, Daniel B. Thompson, Christina Ye Chen, Steven P. DenBaars, Shuji Nakamura and Umesh K. Mishra; UCSB, Santa Barbara, California.

We investigated the direct wafer bonding of a ZnO substrate to a III-nitride light emitting diode (LED) wafer for the purpose of improving light extraction efficiency, which is critically important for improving external quantum efficiency of LED. ZnO has the characteristic advantages of transparency and shape processing compared to conventional Ni/Au alloy for using a transparent p-type electrode. For this study, we used a InGaN/GaN LED grown on a (0001) sapphire substrate by metal-organic chemical vapor deposition and a commercially available n-type conductive ZnO substrate. After surface cleaning the wafers using solvent and acid, the two wafers were joined together and uniaxial pressure of 2 MPa was applied using a fixture. The sample was then loaded into a furnace and heated to 600 °C for 1 h in nitrogen. After this thermal process, the InGaN/GaN LED wafer and ZnO substrate were successfully wafer bonded. Transmittance of the wafer bonded sample was 70 % at 450 nm, which was nearly the same as that of a InGaN/GaN LED on sapphire without ZnO substrate. Current-voltage measurements revealed that the wafer bonded LED has no definite turn-on voltage addition caused by the wafer bonding process.

9:15 AM FF19.5
Enhancement of Light Extraction in Gainn Light-Emitting Diodes by Omni-Directional Reflectors with ITO Nanorod Low-Index Layer. Jong Kyu Kim[1], J. -Q. Xi[2], Hong Luo[2], Jay M. Shah[1], Yangang Xi[2], Thomas Gessmann[1], Jaehee Cho[3], Cheolsoo Sone[3], Yongjo Park[3] and E. Fred Schubert[1,2]; [1]ECSE, Rensselaer Polytechnic Institute, Troy, New York; [2]Physics, Rensselaer

Polytechnic Institute, Troy, New York; [3]Photonics Program Team, Samsung Advanced Institute of Technology, Suwon, South Korea.

The refractive-index contrast is an important figure of merit for dielectric multilayer structures including omnidirectional reflectors (ODRs). Recently, different types of ODRs with high reflectivity, wide stop band, and omnidirectional reflection characteristics have been demonstrated. The ODR is based on the high/low/high complex refractive index of the Ag, a SiO2 low-index layer, and GaN. However, the Ag/SiO2/GaN ODR needs an absorptive semi-transparent current spreading layer between SiO2 and GaN, and an array of micro-contacts enabling electrical conductivity between the semi-transparent layer and Ag through the insulating SiO2 low-index layer, which leads to a decrease in reflectivity of the ODR and an increase in process complexity. This motivates the development of new optical thin films with high transparency, high conductivity, and low refractive index. In this work, enhancement of light extraction in GaN light-emitting diodes (LEDs) employing ODRs with ITO nanorods is presented. The ODR consists of a GaN, an ITO nanorods low-index layer, and an Ag layer. The cross-sectional scanning-electron micrograph clearly shows that the gap between the ITO nanorods is less than 50 nm, i.e. much smaller than the wavelength of visible light, and thus sufficiently small to make scattering negligibly small. The refractive index of ITO nanorods film is measured to be 1.40 at 461 nm, much smaller than that of dense ITO (2.06 at 461 nm) and even smaller than that of SiO2. It is experimentally shown that the GaN/ITO nanorods/Ag ODR has higher reflectivity than Ag reflector, leading to higher light extraction efficiency in the GaInN LEDs with ODRs. Furthermore, the operation voltage of the ODR-LED is $\sim$ 3.3 V at 20 mA, much lower than that of LEDs with Ag contact ($\sim$ 7 V).

9:30 AM FF19.6

High Efficiency Nitride Light Emitting Diodes using Patterned Structures. Cheolsoo Sone[1], Jaehee Cho[1], Jin Seo Im[1], Sukho Yoon[1], Jeong Wook Lee[1], Hyunsoo Kim[1], Joosung Kim[1], Kwang Hyeon Baik[1], Hyung Kun Kim[1], Yusik Kim[1], Yongjo Park[1] and Heonsu Jeon[2]; [1]Photonics Program Team, Samsung Advanced Institute of Technology, Suwon, Kyungki-do, South Korea; [2]School of Physics and Inter-university Semiconductor Research Center, Seoul National University, Seoul, Seoul, South Korea.

The external quantum efficiency of nitride light-emitting diodes (LEDs) grown on sapphire substrates is greatly affected by the internal reflection of lights inside the chip. To prevent total internal reflection of light, several approaches have been successfully adopted such as a truncated-inverted-pyramid LED, a random-textured LED, a micro-patterned LED and so on. Besides the problems related with light extraction, structural defects are easily generated mainly because of large differences in lattice constant between nitride epitaxial layers and sapphire substrates. It is well known that the structural defects are closely related with the internal quantum efficiency of nitride LEDs. In this study, we proposed three kinds of novel nitride LED structures, dielectric embedded nitride structure (DENS), laser hologram submicron patterning and in situ surface roughening, to improve the external quantum efficiency by reducing dislocation density and increasing extraction efficiency, simultaneously. DENS was fabricated by combining defect-selective wet etching, dielectric layer formation inside the etched pattern, and selective growth of nitride on patterned structures. The defect-selective wet etching process was developed by using conventional phosphoric acid and potassium hydroxide solutions, which resulted in random hexagonal pit arrays with densities between 1E6 and 1E7 cm-2. The dielectric layer deposition process followed by etching was optimized to expose the patterns with nitride and dielectric layers on the same plane. LED structures were grown on DENS template by low pressure metal-organic chemical vapor deposition (MOCVD) technique. The optical ray tracing simulation showed that the increase in output power due to DENS was over 80% at least. Two-dimensional square-lattice photonic crystal patterns were generated on top of the GaN surface using laser holography technique. More than two-fold output power enhancement was observed from the resultant devices with the pattern period of 500 nm. Unlike the above two approaches, we tried to fabricate the random surface texturing patterns by adopting in situ SiNx treatment during MOCVD growth process, which resulted in the increase of optical power by 1.4 times. In this presentation, we will discuss the effects of various patterning techniques on the optical and electrical characteristics of nitride LEDs in detail.

9:45 AM FF19.7

Homoepitaxial GaN based laser diodes at 390 nm emission wave length. Stephan Figge, Jens Dennemarck and Detlef Hommel; Institute of Solid State Physics, University of Bremen, Bremen, Bremen, Germany.

Recently the interest raised in homoepitaxy of GaN based light emitting devices due to the expected superior device performance in contrast to the growth on substrates like sapphire. Within the last few years GaN wafers produced from thick HVPE layers grown on sapphire substrates and subsequently seperated from the host substrate became available. In this presentation we will compare GaN-based laser diodes, which were grown by metal organic vapour phase epitaxy on free standing GaN substrates of different material quality and we will compare them against laser diodes grown on sapphire substrates. The laser diodes were grown as separate confinement hetero structures on GaN substrates provided by Lumilog in LED-grade ($>10^8$/cm^2 threading dislocation density) and Laser-grade ($>10^6$/cm^2 threading dislocation denisty) quality. The diodes on sapphire substrates were deposited on MOVPE grown GaN-templates. The L-I characteristics of the laser diodes on GaN substrates revealed lasing in pulsed operation above a threshold current density of approximately 10 kA/cm^2. The maximum achieved duty cycle for laser emission of these diodes was in the range of 50 %, which is much higher than the best duty cycles realized in our laboratory on sapphire substrates (2% duty cycle). The laser diode on LED-grade material showed laser emission at a wavelength of 400 nm, whereas the emission of the diode on laser-grade material was shifted to 390 nm. This shift can be attributed to the better thermal contact of the laser-grade wafer to the susceptor, as this wafer was provided two side-polished in contrast to the LED-grade wafer. Although the bare L-I characteristics show a simular behaviour on both GaN substrate, this shift of the emission to the UV shows that the lower defect density of the laser-grade substrate has a big impact on device operation, as lasing is much harder to achieve in this wavelength range. A further advantage of the GaN substrates is the lower tendency to cracking due to the tensile strain of the AlGaN cladding layers. As the structures on GaN substrate show no cracks at a cladding layer thickness of 500 nm each and a Aluminum content of 8 %, we grew a series of lasers with increasing Aluminum content in order to improve the device performance at 390 nm emission wavelength. The improvements gained in this series will be discussed in detail.

SESSION FF20: Optical Properties
Chair: Alex Cartwright
Thursday Morning, December 1, 2005
Grand Ballroom (Sheraton)

10:15 AM FF20.1

Time-resolved Spectroscopy of Excitons Bound at Shallow Neutral Donors in HVPE GaN. Bo Monemar[1], Plamen P. Paskov[1], Peder Bergman[1], Tadas Malinauskas[2], Kestutis Jarasiunas[2], Alexey A. Toropov[3], Pierre Gibart[4], Bernard Beaumont[4] and Akira Usui[5]; [1]IFM, Linkoping University, Linkoping, Sweden; [2]Institute of Materials Science and Applied Research, Vilnius University, LT-2040 Vilnius, Lithuania; [3]RAN, A F Ioffe Physico-Technical Institute, St Petersburg, Russian Federation; [4]Lumilog SA, F-06220 Vallauris, France; [5]R&D Division, Furukawa Co, Ltd, Tsukuba, Japan.

Time-resolved photoluminescence (TRPL) spectroscopy has been performed in the temperature range 2 K to 300 K on thick (300 micrometers to 1 mm) nominally undoped bulk HVPE grown GaN layers. The PL spectra were recorded in different polarisations (α, σ, π). The layers are n-type due to a residual concentration of O and Si donors. The PL spectra are dominated by the free excitons (FEs) and the two neutral donor bound excitons (DBEs) at about 3.4712 eV and 3.4721 eV at 2 K, assigned to the residual O and Si donors, respectively. The decay curves for both FEs and BEs are nonexponential, with a fast initial decay and a much slower tail at longer times. In high quality samples the decay curve is independent of excitation density, characteristic of the radiative decay. The initial decay time of the FE is about 130 ps at 2K in such samples, the corresponding initial decay time for the DBEs for O and Si is close to 300 ps. Accurate values reflecting the true radiative decay times of the bound excitons are obtained via modelling of the coupled PL transients of FEs and DBEs. At elevated temperatures the long time decay is very similar for FEs and DBEs. We suggest that the slower recombination of the DBEs at longer times may be related to feeding from the dark free exciton polariton states. The different lines corresponding to the so called two-electron transitions for the DBE show a strong variation in decay behaviour, correlating with the corresponding principal DBE states.

10:30 AM FF20.2

Extremely High Internal Quantum Efficiency of InAlGaN Quantum Well with Emission at 336 nm. Hideki Hirayama[1], Yoshiki Yano[3], Misato Shimizu[2], Nakao Akutsu[3], Kou Matsumoto[3] and Hajime Okumura[2]; [1]Advanced Devices Laboratory, RIKEN, Saitama, Japan; [2]AIST, Tsukuba, Japan; [3]Taiyo Nippon Sanso Co. Ltd., Tsukuba, Japan.

Quaternary InAlGaN is very attractive for the emitting region of deep

ultraviolet (UV) light-emitting diodes (LEDs) or laser diodes (LDs), because high efficiency 280-380 nm UV-band emission is obtained at room temperature (RT) due to In-incorporation effects. InAlGaN is considered to be particularly useful for the production of commercially available low-cost deep-UV emitters, since it emits efficiently even it is deposited on sapphire-based templates with high-density threading dislocations (TDs). In this work, we achieved extremely high internal quantum efficiency (IQE) as high as 35% for quaternary InAlGaN quantum well (QW) with emission wavelength at 336 nm. This is the highest IQE value ever reported for deep-UV emission reange. The samples were grown on sapphire (0001) substrates by low pressure metalorganic vapor phase epitaxy (MOVPE). The MOVPE system we used is Taiyo Nippon Sanso Co. Ltd's SR4000 which is designed for the production of InGaN-based blue LEDs and violet LDs (one 4-inch wafer or three 2-inch wafers). We fabricated six periods of Inx1Aly1Ga1-x1-y1N/Inx2Aly2Ga1-x2-y2N multi (M) QWs on GaN buffer layers grown on sapphire substrates. We obtained single-peaked intense photoluminescence (PL) with wavelengths between 320-350 nm at RT from the InAlGaN MQWs. The intensity of the 336 nm UV-emission from the quaternary InAlGaN MQW was as strong as that of 430 nm blue-emission from InxGa1-xN/GaN MQW which was prepared as a reference. The internal quantum efficiency (IQE) of the QW was estimated by comparing the integrated PL intensities measured at low-temperature and at RT. The PL measurement was performed excited by Ar-second harmonics generation (SHG) laser (257nm). The excitation power density was approximately 300W/cm-2. The IQE values estimated for the InAlGaN MQW (336 nm emission) and the InGaN MQW (430 nm emission) were 35% and 38%, respectively. The values of IQE may become larger by using higher excitation power density. In conclusion, we observed extremely high IQE of InAlGaN MQW emitting in deep-UV. The IQE value was estimated to be at least 35% for an InAlGaN MQW with an emission wavelength at 336 nm. From these results, it was demonstrated that InAlGaN QWs are very promising for the realization of high-efficiency deep-UV LEDs or LDs.

10:45 AM FF20.3
Thermalization and Recombination Kinetics of Excitons in thick AlN Epilayers. Till Riemann[1], J. Christen[1], T. Schulze[2], A. Hoffmann[2], K. Balakrishnan[3], N. Fujimoto[3], T. Kitano[3], M. Iwaya[3], S. Kamiyama[3], I. Akasaki[3] and H. Amano[3]; [1]Institute of Experimental Physics, Otto-von-Guericke University Magdeburg, Magdeburg, Germany; [2]Institute of Solid State Physics, Technical University Berlin, Berlin, Germany; [3]21st Century COE "Nano-Factory", Meijo University, Nagoya, Japan.

The near band edge emission (NBE) of a 3.6μm thick AlN layer grown directly on 6H-SiC substrate by metal organic vapor phase epitaxy (at 1350 °C) is analyzed by spatially, spectrally and ps-time resolved cathodoluminescence microscopy (CL) at variable temperature. As confirmed by scanning electron microscopy (SEM), the AlN exhibits a planar surface interrupted by micro-cracks. Additionally, hexagonal micro-craters are found with a density of 10^7 cm^{-2}. NBE CL spectra, spatially integrated over 45μm x 30μm at T=6K, consist of a sharp (FWHM=20meV) line at 5.98eV, superimposed by a high-energy shoulder at 6.00eV. However, in mappings of the CL peak position, a strong spectral modulation of the NBE peak energy is observed. Here, the NBE peak shift perfectly images the crack network: in the vicinity of the micro-cracks a peak position of 6.02eV is determined, while the crack-free regions are characterized by red shifted emission near 5.96eV. To avoid spectral broadening due to this stress-induced peak shift, the NBE temperature dependence was investigated under local e-beam excitation in the perfect crack-free regions. Here, the CL emission is highly homogeneous showing lateral energy fluctuations on a 1 - 2 μm scale leading to an overall standard deviation of σ_E=3.8meV. From the thermalization we can clearly assign the dominant 5.97eV emission at 6K to a bound exciton. At 60K we observe the thermal activation of the high-energy shoulder into a separate emission peak at 5.99eV, identified as the free exciton. The delocalization of the bound exciton leads to an initial blue shift of the NBE emission of 20meV from 5K to 100K. With further temperature rise the spectral red shift of the excitonic CL can be described by the Bose-Einstein-model. An excitonic binding energy of 59meV and a localization energy of 22meV for the bound exciton are derived from the Arrhenius plots. Similar to the temperature dependence, the temporal evolution of the NBE emission was analyzed in the fully stressed regions of the AlN layer. Periodic excitation of the AlN was performed by rectangular e-beam pulses of 30ns length with repetition rate of 1MHz; the overall time resolution is better than 35ps. At 6K, spectrally integrated NBE transients exhibit a fast initial single-exponential drop ($\tau\langle$100ps) followed by a slow decay (τ=2.5ns). This slow decay component clearly deviates from an exponential behavior and is better described by a power law with exponents ranging from -1 to -1.5. When spectrally scanning over the NBE emission at T=6K, we preferentially find the slow decay component at high energies, coinciding with the spectral position of the free exciton. The slow component of the NBE decay vanishes with rising temperature, leading to a single-exponential decay over three orders of magnitude above T=40K. This corresponds quantitatively with the localization of the free exciton in the local stress induced lateral potential minima (σ_E=3.8meV $\Rightarrow$ T_A=45K).

11:00 AM FF20.4
Strong light-matter coupling at room temperature in GaN microcavities with epitaxial (Al,Ga)N Bragg mirrors grown on silicon. Ian Robert Sellers[1], Fabrice Semond[1], Mathieu Leroux[1], Jean Massies[1], Joel Leymarie[2], Pierre Disseix[2], Amie Vasson[2] and Anne Line Henneghien[2]; [1]CRHEA-CNRS, Valbonne, France; [2]LASMEA, Clermont Ferrand, France.

We present both experimental and theoretical results demonstrating strong light-matter coupling in bulk GaN microcavities at room-temperature. The microcavity structure consists of a ?/2-GaN active region with a 7 period AlN/Al0.2Ga0.8N distributed Bragg reflector (DBR) grown by molecular beam epitaxy directly on Si(111) [1]. The stop-band of the reflectivity spectrum is centred at 3.48eV with a peak reflectivity of 91% and stop-band width of ~450meV. The experimental reflectivity is well reproduced using numerical simulations of the structure, indicating a high structural quality for the DBR despite the large lattice and thermal mismatch between the silicon substrate and the DBR layers. Further evidence of the quality of the DBR is displayed in high resolution atomic force microscopy (AFM) images, which show a low surface roughness of ~0.5nm over an area of 1?m2 on the DBR surface. The AFM images also clearly indicate that the growth of the AlN/Al0.2Ga0.8N layers follows a conventional hexagonal step-like process, well known in the nitride system [2]. The cavity is completed by the thermal evaporation of a transparent aluminium mirror above the bulk GaN active layer, through which the reflectivity and luminescence spectra are measured. The strong-coupling regime is observed at low temperature with a Rabi-energy of ~50meV, and preserved up to room temperature. This results from a combination of the narrow exciton and photon linewidths 19meV and 57meV respectively, and the large Rabi-energy. Evidence of strong coupling is also shown in temperature dependent reflectivity measurements. Furthermore, at low temperature, where the thermal broadening of excitons is negligible, we observe both the A and B-excitonic features of the GaN cavity and their respective anti-crossing with the photonic mode. Such results clearly indicate the high quality of our GaN material, and the large binding energy and oscillator strength of the excitons, as theoretically predicted [3]. The observation of a large Rabi-energy of 50meV at 300K, with narrow exciton and photonic linewidths, offers the potential of observing stimulated scattering effects at room temperature. This opens up the possibility of producing a new generation of threshold-less lasers, which are based on the strong-coupling regime operating at 300K, which is not possible in conventional III-V systems. [1] F. Semond et al. phys. stat. sol. (a) 183 p163 (2001) [2] N. Grandjean & J. Massies. Appl. Phys. Lett. 71. p1816 (1997) [3] A. Kavokin et al. Appl. Phys. Lett. 72 p2880 (1998) * electronic mail; Ian.Sellers@crhea.cnrs.fr

11:15 AM FF20.5
Optical and Structural Properties of Al0.12Ga0.88N/Al0.5Ga0.5N Microcavities Containing GaN Quantum Wells. Oleg Mitrofanov[1], Stefan Schmult[1], Michael J. Manfra[1] and Richard J. Molnar[2]; [1]Bell Labs, Lucent Technologies, Murray Hill, New Jersey; [2]Lincoln Lab, MIT, Boston, Massachusetts.

Strong light-matter coupling and a wide bandgap range of the Nitride-based alloys make GaN systems attractive for optical applications. The large lattice mismatch within the family of Nitride alloys, however, introduces many extended defects, which degrade optical quality of the heterostructures and substantially increases inhomogeneous broadenning of excitons. We discuss optical and structural properties of MBE grown microcavities consisting of Al0.12Ga0.88N/Al0.5Ga0.5N distributed Bragg reflectors (DBR) and GaN quantum wells. To reduce the number of defects the microcavity structure is grown on GaN templates. TEM studies show extremely smooth interfaces and negligible extended defect generation. Small inhomogeneous broadening of excitons in GaN quantum wells results in a large light-exciton coupling strength. In order to further reduce the lattice mismatch induced strain in the structure we incorporate In into the DBR layers. We examine the possibility of high quality Bragg reflectors in the spectral range of the GaN quantum well excitons.

11:30 AM FF20.6
Optical properties of GaN Photonic Crystal Membrane Nanocavities at Blue Wavelengths. Yong-Seok Choi[1], Cedrik Meier[2], Rajat Sharma[2], Kevin Hennessy[3], Elaine Haberer[2], Shuji Nakamura[2] and Evelyn L Hu[1,2,3]; [1]California NanoSystems Institute, University of California, Santa Barbara, California; [2]Materials Department, University of California, Santa Barbara, California; [3]Department of Electrical and Computer Engineerings, University of California, Santa Barbara, California.

Research on photonic crystal (PC) nanocavities opens a wider range of applications for GaN material systems in the short wavelengths from the ultraviolet to the green. High-Q nanocavities can lead to low-threshold lasers with a possibility of high density integration with filters and waveguides. The strong coupling regime can also be easily achieved considering the high-Q/V and the large oscillator strength of InGaN quantum well excitons. Furthermore, GaN-based quantum dots (QDs) embedded in high-Q 2D PC nanocavities will facilitate the study of cavity quantum electrodynamics and single photon sources at room temperature with the virtue of the deep confinement resulting from the large GaN bandgap. From the processing point of view, GaN-based PC nanocavities pose a number of challenges. Techniques for well-controlled, selective, low damage etching of these materials are still being developed. Moreover, PCs in GaN require higher precision lithography and etching techniques than what are required for GaAs or InP-based PCs. To achieve good optical confinement in the low refractive index (n$\sim$2.6) PC nanocavities, it is indispensable to use free-standing membrane structures, which until recently have been particularly difficult to fabricate in GaN materials. The development of a bandgap-selective photoelectrochemical (PEC) etching technique, combined with a cleverly designed InGaN sacrificial layer, has allowed the creation of free-standing structures for high-Q microdisk lasers, air-gap distributed Bragg reflectors, and PC membrane nanocavities. In this paper, we have investigated the PC membrane nanocavity, which consists of several missing holes in the Gamma-K direction of the triangular-lattice PC structure. We report the characteristics of the resonance modes, their tuning behavior, and design and fabrication issues to achieve high-Q modes at the wavelength of about 480nm.

SESSION FF21: Bulk + HVPE
Chair: Dan Koleske
Thursday Afternoon, December 1, 2005
Grand Ballroom (Sheraton)

1:30 PM FF21.1
Growth of Large AlN Single Crystals along the [0001] Direction. Ziad Georges Herro, Dejin Zhuang, Raoul Schlesser and Zlatko Sitar; Materials Science And Engineering, North Carolina State University, RALEIGH, North Carolina.

Aluminum nitride (AlN) possesses a number of excellent properties that make it highly desirable for use as a III-nitride substrate material. Due to its high thermal conductivity, high chemical stability, and wide bandgap, AlN is suitable for fabrication of high-power/high-temperature electronic and optoelectronic devices. Although the number of AlN research groups increased over the past decade reproducible production of large AlN crystals using a sublimation growth scheme has not yet been reported. This is due to three major problems: (i) The lack of large-size, single crystalline AlN seeds; (ii) contamination issues (oxygen and carbon impurities) affecting high-temperature sublimation growth, and (iii) the need of adequate control of the thermal field inside the growth chamber, which is relevant due to the strong dependence of N2(g) and Al(g) partial pressures on temperature (driving force). In this study we will present our efforts to overcome these problems; (0001)-oriented seeds of 3.5 mm in diameter were obtained using a self-seeded process (grain selection mechanism) and used in further growth runs. The N-face was found to be suitable for growth and large crystals of 15 mm in diameter were obtained after several consecutive growth runs. AFM microscopy showed step heights of 2 to 6 lattice parameter units in c-direction of AlN. On the Al-face numerous growth centers appeared to have step heights of 1c. All crystals were grown using graphite insulation, which enables proper control over the thermal field geometry, and allows tailoring of very low axial temperature gradients. The role of C contamination (from graphite insulation) and its reduction to low levels will be discussed in the presentation. Oxygen contamination and subsequent Al2O3 formation was reduced by sintering the powder source at growth temperatures for 20 hours. Oxygen levels were reduced below 100 ppm (weight) in the powder source and the grown crystals. AlN single crystals of 15 mm in diameter were obtained. Key requirements for the reproducible growth of large, high-quality AlN crystals include perfect control of the thermal profile inside the reactor hot zone, reduction of impurities and seeded growth enabling the expansion of single crystals grown from comparatively small seeds.

1:45 PM FF21.2
Oxidation of Aluminum Nitride for Defect Characterization. Kyle Taggart[1], James H. Edgar[1], Zheng Gu[1], Jharna Chaudhuri[2], L. Nyakiti[2], R. G. Lee[2] and J. Wen[3]; [1]Chemical Engineering, Kansas State University, Manhattan, Kansas; [2]Mechanical Engineering, Texas Tech University, Lubbock, Texas; [3]Center for Microanalysis of Materials, University of Illinois, Urbana, Illinois.

The thermal oxidation of aluminum nitride was developed as a means to study defects in bulk aluminum nitride crystals. The kinetics was established for wet and dry oxidation of low defect density AlN crystals produced by sublimation-recombination crystal growth. With low defect density crystals, the effects of individual defects on the oxidation rate can be observed. The oxidation rate is dependent on the crystal's orientation, polarity, stress, and surface condition, thus oxidation decorates grain boundaries, polishing scratches, and inversion domains by producing oxide layers of different thicknesses. Examples include the nearly twice as fast oxidation of nitrogen polar crystals compared to aluminum polar crystals and the increased oxidation rate in the vicinity of dislocations. Low temperature (800 C) dry oxidation produced an amorphous oxide layer and generated a high density of defects (vacancies, stacking faults, and dislocations) in the nitride near the oxide/nitride interface, as observed by cross-sectional transmission electron microscopy. In contrast, high temperature oxidation (1000 C) produced a crystalline oxide layer, and left the nitride free of observable defects. Differences in the chemical state of the nitrogen in the oxide produced at high and low temperatures were detected by electron energy loss spectroscopy. The difference in the wet and dry oxidation rates increased with a reduction in temperature.

2:00 PM FF21.3
Ammonothermal growth of GaN in an autoclave with ϕ 40 mm capacity. Tadao Hashimoto[1,2], Makoto Saito[2,3], Kenji Fujito[3], Feng Wu[1,2], Paul T Fini[1,2], James S Speck[1,2] and Shuji Nakamura[1,2]; [1]Materials, University of California, Santa Barbara, Santa Barbara, California; [2]ERATO/JST, UCSB group, Santa Barbara, California; [3]Mitsubishi Chemical Corporation, Minatoku, Tokyo, Japan.

Recently bulk GaN growth has been an intensively researched area because GaN wafers sliced from bulk crystals will have tremendous benefits for GaN-based devices. Ammonothermal growth, which is categorized as solution growth in a supercritical fluid, has an advantage over other bulk growth methods due to its outstanding scalablility. Several groups have reported GaN growth by an ammonothermal method, however, all of these reports have not demonstrated its excellence of scalability. In this paper, we will report on growth of GaN on large area ($\sim$2 x 3 cm^2) GaN seeds in an autoclave whose capacity is about ϕ 40 mm. GaN was grown on a free-standing GaN seeds which had been prepared by hydride vapor phase epitaxy (HVPE) followed by laser lift-off of sapphire substrate. The metallic Ga was placed in a low-temperature zone (500-580°C) and the seed crystals were placed in a high-temperature zone (550-600°C). Growth pressure was in the range between 138 and 200 MPa (20,000 and 30,000 psi, respectively). Sodium amide and sodium iodide were used as mineralizers. The maximum size of the GaN obtained so far is about 2 cm x 3 cm, which is currently limited by the availability of HVPE-grown seed crystals. The thickness of ammonothermally grown film ranged from 4 to 45 μm depending on growth conditions. The fastest growth rate was about 13 μm/day, which is getting closer to target growth rate (70 μm/day) necessary for commercialization of this method. A cross-sectional transmission electron microscopy (TEM) study revealed high density of dislocations and voids at the interface between seed crystal and grown film. These crystal defects healed out after about 45 μm-growth, resulting in the estimated threading dislocation density of 2 x 10^9 cm^{-2}.

2:15 PM FF21.4
High quality GaN layers grown on slightly miscut sapphire wafers. Peter Brueckner[1], Martin Feneberg[2], Klaus Thonke[2], Frank Habel[3] and Ferdinand Scholz[1]; [1]Optoelectronics Department, University of Ulm, Ulm, Germany; [2]Semiconductor Physics Department, University of Ulm, Ulm, Germany; [3]Freiberger Compound Materials GmbH, Freiberg, Germany.

The improvement of GaN based electronic and optoelectronic devices is still limited by high defect densities as a consequence of the fact that they have to be grown on foreign substrates like sapphire or SiC, because high quality GaN-substrates are not yet really available. Therefore, the heteroepitaxial growth of thick GaN layers by hydride vapor phase epitaxy (HVPE) which can be used as quasi-substrates for device epitaxy is being investigated by many groups. Our current studies focus on the deposition of thick uncracked GaN layers with excellent surface morphology, low defect density and low or zero bowing, which are still the major challenges. The latter feature requires free-standing GaN by removing the foreign substrate after the HVPE process. We performed our growth studies in a commercial HVPE system with a horizontal quartz reactor using MOVPE grown templates on 2" sapphire wafers. By optimizing our growth conditions, we were able to grow crack-free GaN layers up to thicknesses of more than 100μm on 2" wafers, which exhibited excellent electrical and optical properties [1]. Much thicker layers exceeding 300μm could be grown crack-free by using templates covered with a stripe mask as it is used for epitaxial lateral overgrowth. The surface morphology of HVPE layers typically shows a

high density of pyramidal structures which makes some polishing process necessary before their subsequent use in device epitaxy. We found that a slight misorientation of the substrate totally suppresses the development of such pyramids resulting in a surface flatness comparable to MOVPE grown layers. The stronger bowing of these layers compared to those on exactly oriented wafers indicates lower strain relaxation, certainly due to their lower defect density. Best results have been obtained on templates with misorientations between 0.3° and 0.6°, depending slightly on the other growth conditions. Furthermore, we investigated different approaches towards free-standing GaN by separating our thick HVPE-grown layers in-situ during cooling-down after the epitaxial process. One way is the growth on masked templates where the geometry and the filling factor can be optimized for best self-separation. Up to now, large pieces (although not yet complete wafers) of free-standing GaN have been obtained, which exhibited very low defect densities in the mid 1E6cm-2, and extremely narrow photoluminescence lines of the bound exciton transition with halfwidth below 800μeV. Moreover, we observed a reduction of bowing by a factor of 3. Similar results have been obtained by inserting a low temperature interlayer near the substrate. [1] F. Habel, P. Brueckner, J-D. Tsay, W.-Y. Liu, F. Scholz, D. Schmitz, M. Heuken, phys. stat. sol. (c) 2 (7) 2049-2052 (2005)

2:30 PM FF21.5
High-Quality AlN Layers Grown Using an Inverted HVPE Reactor. Rakesh B. Jain[1,2], Jiawei Li[1], Arulchakkaravarthi Arjunan[1], Mikhail Gaevski[1], Edmundas Kuokstis[1], Jinwei Yang[1] and M. Asif Khan[1]; [1]Department of Electrical Engineering, University of South Carolina, Columbia, South Carolina; [2]Sensor Electronic Technology, Inc., Columbia, South Carolina.

We report the growth of high-quality AlN layers by hydride vapor phase epitaxy (HVPE) using a vertical reactor with an inverted geometry. The reactor combines an rf-heated growth zone and a resistively heated source region thereby enabling metalorganic chemical vapor deposition (MOCVD) and HVPE on the same substrate without breaking vacuum. High-purity Al metal source maintained at 500° C with HCl carrier gas and NH_3 were used as the precursors for the reported experiments. Migration enhanced MOCVD deposited 0.1 μm thick AlN films (over two inch sapphire substrates) were used as templates for the growths. Completely transparent HVPE AlN films could be grown at rates ranging from 2 to 20 μm/hr. However, the film quality was found to decline with increasing growth rates. The quality was then optimized for films deposited at a growth rate of 5 μm/hr by varying growth parameters such as temperature, pressure, and the V/III ratio. This yielded 3-5 μm thick films with (0002) X-ray rocking curves having a FWHM as low as 160 arcsec. Room temperature photoluminescence spectra show sharp band-edge emissions at 207 nm with the narrowest FWHM of 150 meV. For layers grown at temperatures in excess of 1100° C, the deep level emissions around 260 nm were significantly suppressed. RMS surface roughness of as-grown samples calculated by atomic force microscopy (AFM) was less than 2 nm. The morphology and defect density of the HVPE grown AlN layers was also investigated by wet chemical etching. The etching reveals hexagonal column-like features which are observable by both scanning electron microscopy and AFM. Cathodoluminescence and Energy Dispersive X-ray analyses were used to identify the composition of particles present on the as-grown sample surface. The etch pits caused by particles as well as threading dislocations were also found to be hexagonal-shaped. Etch pit density for a 2 μm thick HVPE AlN film was 2x10^8 cm^{-2}, which is at least one to two orders of magnitude smaller than MOCVD grown AlN films. Details of the growth procedures and characterization results will be discussed. In addition preliminary results of MOCVD grown device structures on HVPE AlN layers using the new MOCVD/HVPE combinational reactor will also be presented.

SESSION FF22: Structural
Chair: Michael Dudley
Thursday Afternoon, December 1, 2005
Grand Ballroom (Sheraton)

3:15 PM *FF22.1
Structure analysis of ELO-GaN grown on sapphire using the x-ray micro-beam of 8-GeV storage ring. Takao Miyajima[1], Shu Goto[2], Yoshihiro Kudo[3], Shigetaka Tomiya[3], Shingo Takeda[4], Hideaki Kurihara[4], Kyoko Watanabe[4], Madomi Kato[4], Nobuhide Hara[4], Yoshiyuki Tsusaka[4], Junji Matsui[4], Masao Ikeda[2] and Hironobu Narui[1]; [1]Materials Laboratories, Sony Corp., Atsugi, Kanagawa, Japan; [2]Shiroishi Laser Ctr., MSNC, Sony Corp., Shiroishi, Miyagi, Japan; [3]Materials Analysis Ctr., Sony EMCS Corp., Atsugi, Kanagawa, Japan; [4]Graduate School of Science, Himeji Institute of Technology, Kamigori-cho, Hyogo, Japan.

By growing a GaN-based laser diode (LD) on epitaxially laterally overgrown GaN (ELO-GaN) [1, 2], we demonstrated a practical lifetime of 15,000 hours with an output power of 30mW at a temperature of 60°C [3]. ELO-GaN strongly contributed to this work by reducing the threading-dislocation density to 10^6 cm^{-2} and providing a smooth cleaved facet. The structure had been previously analyzed using TEM and standard x-ray diffraction (XRD) measurements [4], but these measurements only clarified the structure at nm scale and mm scale, respectively. Here, we analyze the μm-scale structure of ELO-GaN grown on sapphire using a 2x4 μm^2 x-ray micro-beam [5], which became available using the bright x-ray source of the 8-GeV storage ring (SPring-8). The GaN (0 0 0 12) rocking curve of the wing region (13.5μm wide) had a sharp peak with a FWHM of 46 arcsec, but that of the seed region (2.5μm wide) had several broad peaks. This peak-narrowing is caused by the reduction in threading dislocation density as well as to an increase in homogeneity of the GaN c-axis tilts in the wing region. It has been reported that the angle of c-axis tilts increased in ELO-GaN with an SiO_2 mask. The angle of tilt is generally dependent on the interaction of GaN and the mask material during the growth [4] but even in ELO-GaN grown on sapphire without a SiO_2 mask, a small-angle tilts were observed. The wing-region GaN hang down from the seed region GaN at a tilt of 81.5 arcsec. A similar tilting was observed in another ELO-GaN sample without coalescence. In this sample, ELO wing regions did not coalesce during growth. We concluded, therefore, that the c-axis tilting of ELO-GaN (without SiO_2 mask) was caused by the thermal strain at the interface between GaN and sapphire in the seed region. This conclusion is supported by another finding that ELO-GaN grown on SiC showed c-axis tilting in the opposite direction -up [6]. The grain size of ELO-GaN with and without coalescence was estimated by mapping the rocking curve intensity at an equivalent tilt angle. It was typically 5μm x 5μm in the wing region of ELO-GaN with coalescence and 10μm x 10μm in the wing region of another ELO-GaN sample without coalescence. We therefore conclude that the homogeneity of GaN c-axis tilting is destroyed when the wing regions of ELO-GaN coalesce. We believe that this inhomogeneity of GaN c-axis tilting and grain size strongly affect the generation of mixed and screw dislocations, the surface growth mode, the In compositional fluctuation of the GaInN active layer of GaN-based LDs, and the device performance including lifetime. [1] T. Zheleva et al., MRS Internet J. Nitride Semicond. Res. 4S1 (1999) G3.38. [2] T. Tojyo et al., Jpn.J.Appl.Phys. 40 (2001) 3206. [3] T. Tojyo et al., Jpn.J.Appl.Phys. 41 (2002) 1829. [4] S. Tomiya et al., phys.stat.sol. (a) 188 (2001) 69. [5] T. Miyajima et al., phys.stat.sol. (b) 240 (2003) 285. [6] R.I. Barabash et al., IWN2004, Pittsburgh 2004.

3:45 PM FF22.2
Intersecting basal plane and prismatic stacking fault structures and their formation mechanisms in GaN. Jie Bai and Michael Dudley; SUNY, Stony Brook, Stony Brook, New York.

In this paper, a systematic study is presented of intersecting planar boundary structures observed in a GaN epifilm grown on a vicinal 6H-SiC substrate (offcut towards [1 10]) with an AlN buffer. These structures are shown to comprise stacking faults that fold back and forth from the basal plane (I1 Basal Plane Faults; BSFs) to the prismatic plane (Prismatic Stacking Faults; PSFs). The PSFs , with fault vector ?<10 1> are shown to nucleate in high densities at steps on the substrate surface as a consequence of the different stacking sequences exposed on either side of the step. Once nucleated, PSFs intersecting the vertical step risers in the AlN buffer and eventually in the GaN film are replicated during the predominantly step flow growth and propagate into the growing crystal. As a consequence of the different growth rates experienced on either side of the intersection of a PSF with a vertical step riser, the PSF may be redirected onto an equivalent {11 0} plane, leaving an I1 BSF between the bottom of the redirected section of PSF and the top of that portion of the original PSF which was below the terrace. This leads to the formation of folded PSF/BSF fault structures which exhibit various configurations. Such folded stacking faults enclose domains which have different stacking sequences. Stair rod dislocations (SRDs) with various characters are observed to form at the intersections of these various faults. These SRDs may play roles in both the photoluminescence properties and strain relaxation processes in the GaN film.

4:00 PM FF22.3
Dislocation Reduction and Structural Properties of GaN layers Grown on N$^+$-implanted AlN/Si (111) Substrates. Muhammad Jamil, James R. Grandusky, Vibhu Jindal, Eric Irrisou and Fatemeh Shahedipour-Sandvik; Optoelectronics, College of Nanoscale Science and Engineering, University at Albany-State University of New York, Albany, New York.

In this work we present an alternative scheme to the growth of III-Nitride layers on Silicon substrate that not only addresses crack formation but helps in reduction of high dislocation density in the layers under same processing steps. The effects of N$^+$ ion implantation of AlN/Si (111) substrate on the structural and optical

properties of the overgrown GaN film have been investigated. Results for moderate increase in crack separation using the scheme have been reported elsewhere.† We show that this new scheme results in complete elimination of cracks, a direct result of thermal expansion coefficient mismatch between the epilayer and the substrate. A significant reduction in dislocation defect density and strain in the GaN films on engineered substrates as compared to as grown GaN layers will be presented. Temperature and excitation intensity dependent PL has been used to investigate the impact of implantation conditions (energy and dose) on stability of defects. High resolution X-rays diffraction of GaN films on engineered substrates show improvement in crystal quality confirming the results of etch pit density measurement to show the reduction in dislocation defects for optimized processing conditions. †M. Jamil, J. R. Grandusky, V. Jindal and F. Shahedipour-Sandvik, submitted to APL 2005

4:15 PM FF22.4
Electronic properties of non-stoichiometric dislocation cores in GaN. Liverios Lymperakis and Joerg Neugebauer; Computational Materials Design Department, Max-Planck-Institut fuer Eisenforschung GmbH, Duesseldorf, Germany.

The electronic and optical properties of dislocations in GaN have been and still are one of the most controversial issues in the field of group III-Nitrides. Although the origin of these extended defects is well known (they are caused by the lack of a suitable lattice and thermal matched substrate), their atomic structure, chemical nature and electronic properties are poorly understood. A number of possible mechanisms can cause the electrical activity of dislocations in GaN: Shallow states that originate from the core region can be induced in the gap. As recently has been shown by us the huge strain field around the dislocation core can cause metallization and may induce deep states in the gap[1]. Moreover, Ga- or N- vacancies can be trapped by the core and/or the strain field and affect the electronic properties of the material. Non-stoichiometric cores are present for highly doped material (*n*- as well as *p*- type doping) and for Ga- or N- rich conditions. In this work we study the effect Ga- and N- vacancies have on the core geometry and the optical properties of edge type dislocations in GaN. In a previous work we have developed an $ab-initio$ based multiscale approach that combines elements of Density Functional Theory (DFT), empirical potentials, and continuum elasticity theory[1]. Based on this approach we are able to treat systems consisting of a few 10^5 atoms with $ab-initio$ accuracy. Here we use the multiscale approach to study the formation of Ga- and N- vacancies at various positions in the strain field around the dislocation line. We find that when vacancies are introduced into the core, they strongly affect the atomic geometry of the core. We also find that vacancies may and will become important under extreme Ga-rich conditions (which are characteristic for MBE growth) and/or for highly doped material where vacancies may become charged and may act as compensating centers. Based on our results we discuss the effect dislocations have on the optical properties of epitaxially grown films for different growth conditions and different growth techniques. Financial support by: DFG-research group "Nitride based QD-lasers", University of Bremen. [1] L. Lymperakis, J. Neugebauer, M. Albrecht, T. Remmele, and H.P. Strunk, Strain induced metallization and deep electronic states around threading dislocations in GaN, Phys. Rev. Lett. **93**, 196401 (2004).

4:30 PM FF22.5
A New Mechanism for the Formation of Nanopipes in Gallium Nitride. Michael E. Hawkridge and David Cherns; Physics, University of Bristol, Bristol, United Kingdom.

The formation of open core dislocations (nanopipes) in GaN has been long debated. Although early work showed that screw dislocations in MOCVD-grown material were open core, more recent work has shown that edge and mixed dislocations can be open core in heavily Mg-doped GaN grown by MOCVD and mixed dislocations can be open core in GaN grown by MBE under Ga-rich conditions. These results suggest that impurities play a role. In this paper, we report evidence that oxygen plays an important role in the formation of open core dislocations in GaN grown by hydride vapour phase epitaxy. Electron microscopy studies were carried out on GaN layers of varying thickness grown on (0001) sapphire substrates. Transmission electron microscope studies on plan-view and cross-sectional samples showed varying core structures of screw dislocations between open cores (nanopipes) and closed cores, with irregular variations between the two observed along the length of many dislocations. New evidence was found demonstrating that the equilibrium structure of screw dislocations is a closed core. Some isolated open structures were also observed that were not associated with any dislocation. Electron energy loss spectroscopy combined with high resolution imaging performed in the Daresbury SuperStem, UK, showed the presence of substantial oxygen around open core dislocations, coinciding with a reduction in the nitrogen signal. Our analysis suggested that the oxygen was concentrated within a few atomic layers of the nanopipe surfaces. Quantitative analysis of the data suggested that nearly 2 monolayers of oxygen had replaced nitrogen at the walls of the open core. In contrast, closed core dislocations showed little evidence of oxygen presence. The paper will discuss the role of the oxygen in nanopipe formation. It is argued that the TEM and STEM results, taken together provide strong evidence for a model where the formation of nanopipes in GaN is controlled by oxygen segregation by surface diffusion to pits predominantly, but not exclusively, associated with dislocations. There is evidence that formation of the irregular variation between open and closed cores is a result of post-growth collapse of the nanopipes, rather than dependency on the local concentrations of surface oxygen available. The implication of the results in understanding the electronic behavior of dislocations is also discussed.

4:45 PM FF22.6
Interfaces and Defects in Nitride based Distributed Bragg Reflectors for Vertical Cavity Surface Emitting Lasers using an AlN/GaN Superlattice. Roland Kroeger, Carsten Kruse, Henning Lohmeyer, Juergen Gutowski, Detlef Hommel and Andreas Rosenauer; Institute of Solid State Physics, University of Bremen, Bremen, Germany.

The topic of nitride based alloys for vertical cavity surface emitting lasers (VCSELs) in the blue-violet spectral region is currently a major research issue especially due to their scaleablity. Although materials with sufficiently high index contrast (i.e. AlN and GaN) are available many obstacles have to be overcome for the realization of high quality distributed Bragg reflectors (DBR) required for such VCSEL structures. These obstacles concern line defects and planar defects caused by the high lattice mismatch, surface roughening and the homogeneity of the chemical composition, which all affect the optical properties of the VCSEL structure. This work presents results of a microstructural investigation of DBRs grown by molecular beam epitaxy (MBE) using alternating layers of GaN and a GaN/AlN superlattice to reduce strain related cracking, which occurs if mirror pairs of alternating AlN and GaN layers would be used. The DBRs are deposited on top of a 2 μm thick GaN layer, prepared by metal organic vapor phase epitaxy using a sapphire substrate. It is found that films grown at high temperatures (850 °C) show severe cracking and roughening of the interfaces, whereas films grown at lower temperatures (650 °C) reveal no macroscopic cracks and appear optically smooth. However, room temperature reflectivity measurements for a 30 fold stack of mirror pairs exhibits maximum reflectivity values of only 0.8 at a wavelength of 420 nm although values of 0.99 could be expected. Photoluminescence measurements show a pronounced emission band close to the targeted wavelength, which could indicate residual absorption. Moreover, the reflectivity decreases if the number of pairs is increased, although no macroscopic cracks are observable. The films are largely relaxed as is confirmed by X-ray diffraction measurements. To study the possible presence of defects in the structure transmission electron microscopy (TEM) are used to investigate a superlattice consisting of 200 alternating layers of 0.65 nm GaN and 1.25 nm AlN (resulting in an average Al mole fraction of 0.6). Plan view TEM lamellas of different thickness are prepared by the focused ion beam (FIB) technique from the superlattice structure and for comparison from the GaN sublayer. Even in the thinnest lamella (50 nm thick) a high density of defects (dislocation loops and threading dislocations) running at least partially in the 0002 plane are found, which are absent in the GaN sublayer. For a thicker lamella (about 150 nm) lateral defect distances below 500 nm are observed giving rise to the assumption that these defects are formed due to the strain and constitute the origin of absorption inside the VCSEL structures. A strain state analysis of high resolution TEM images show GaN clusters rather than smooth GaN layers. This might be connected to the overall strain distribution inside the DBRs. A comparison with results obtained for fully strained DBR structures grown on AlGaN sublayers is performed.

SESSION FF23: Poster Session: Optical Properties
Chairs: Leah Bergman and Nicolas Grandjean
Thursday Evening, December 1, 2005
8:00 PM
Exhibition Hall D (Hynes)

FF23.1
Abstract Withdrawn

FF23.2
Cathodoluminescence micro-analysis of AlN MOVPE-grown on sapphire substrate. Juergen Christen, Till Riemann, Armin Dadgar, Juergen Blaesing, Thomas Hempel and Alois Krost; Institute of Experimental Physics, Magdeburg University, Magdeburg, Germany.

Thick AlN layers are microscopically analyzed using spatially and spectrally resolved cathodoluminescence (CL) microscopy. The AlN layers were grown by metal organic vapor phase epitaxy (MOVPE) on sapphire substrate in an AIXTRON AIX 200/4 RF-S reactor using TMAl and NH_3 in a hydrogen atmosphere at 70 mbar and a V/III ratio around 400. After a 25 nm low-temperature AlN seed layer on sapphire the 1- 2.5μm thick AlN layer was grown at ~40°C higher growth temperature as for standard GaN layers. In-situ curvature measurements evidence that the AlN layer grows under strong tensile stress and still is under weak tensile stress after cooling. As confirmed by scanning electron microscopy (SEM), the samples exhibit a planar surface morphology interrupted by micro-cracks. Additionally, micro-craters are found with a density of 10^7 cm^{-2}. Two types of cracks can be distinguished: wide cracks with clearly defined tilted sidewalls, indicating their formation during the MOVPE growth process, and small micro-cracks almost not visible in SEM probably formed during cool-down from growth temperature. At T=5K the spatially integrated CL spectra are dominated by the narrow (FWHM = 50meV) line of the near band edge emission (NBE) at 5.947eV. An additional weak, broad CL band is centered around 3.33eV and CL microscopy clearly identifies the micro-craters as local origin of this defect luminescence. In mappings of the CL peak position (CL wavelength imaging), a strong spectral modulation of the NBE emission energy is observed. The NBE peak shift perfectly images the crack network: while the crack-free regions are characterized by a strongly red shifted emission near 5.849eV, indicating tensile stress, a pronounced blue shift of several 10meV is observed in the vicinity of the micro-cracks visualizing the relaxation of the tensile stress. In order to avoid spectral broadening by this stress-induced peak shift the temperature dependence of CL NBE was investigated under local e-beam excitation in the perfect and crack-free, tensile stressed regions. As a result, the dominant 5.834eV emission at 7K is assigned to a bound exciton. The lateral fluctuation over an area of 27μm x 27 μm gives a standard variation of σ_E=6meV. At around 80K we observe the thermal activation of a separate emission peak at 18meV higher energy, identified as the free exciton. The delocalization of the bound exciton leads to an initial blue shift of the NBE emission of 18meV from 5K to 140K. With further temperature rise the spectral red shift of the excitonic CL can be described by the Bose-Einstein-model. The Arrhenius fit yields a localization energy of 17meV and a thermal activation energy of 6meV confirming the previous results and gives an excitonic binding energy of 59meV. The possible impact of In as surfactand enhancing a smooth AlN growth is discussed.

FF23.3

Polarized Photoluminescence Study on AlGaN Of AlGaN/GaN Heterostructure. Sachio Kitagawa[1], Kenichi Kosaka[1], Tadayoshi Tsuchiya[3], Akira Suzuki[2,3], Tsutomu Araki[1] and Yasushi Nanishi[1]; [1]Dept. of Photonics, Ritsumeikan Univ., Kusatsu, Shiga, Japan; [2]Res.Org.of Sci & Eng., Ritsumeikan Univ., Kusatsu, Shiga, Japan; [3]Advanced HF Device R&D Center, R&D Association for Future Electron Devices, Kusatsu, Shiga, Japan.

AlGaN/GaN heterostructures have been employed in electronic devices such as a heterostructure field-effect transistor (HFET) and optical devices. Usually AlGaN of AlGaN/GaN HFET structure has tensile strain to enhance 2DEG formation by piezoelectric polarization. Therefore, it is important to understand basic properties of strained AlGaN. In this paper, we characterized, for the first time, polarization in the strained $Al_xGa_{1-x}N$ of AlGaN/GaN HFET structure by using polarization-resolved photoluminescence (PL) spectroscopy. $Al_xGa_{1-x}N$/GaN HFET structures were grown on sapphire by metalorganic chemical vapor deposition (MOCVD). Al mole fraction and thickness of $Al_xGa_{1-x}N$ determined by X-ray diffraction were 0.23∼0.32 and ≅30 nm, respectively. Free-standing GaN grown by hydride vapor phase epitaxy (HVPE) was also used as a reference. The strain in $Al_xGa_{1-x}N$ of AlGaN/GaN were characterized by X-ray reciprocal space mapping (RSM). PL spectra were measured between 5K∼300K. The 244.0 nm line of a cw Ar second-harmonic generation (Ar-SHG) laser (5mW) was used as an excitation source. The PL emission with either E//c or E⊥c polarization was collected using polarizer in front of the monochromator at room-temperature (RT). The RSM results showed that AlGaN was coherently grown on GaN, that is, the AlGaN was completely strained under tensile stress. We measured PL spectra of $Al_{0.28}Ga_{0.72}N$ of AlGaN /GaN HFET as a function of temperature from 5K to 300K. We observed two emission peaks in the near-band-gap emission region. Energy separation between these two emission peaks was approximately 40 meV. On the other hand, we observed each emission with the polarization of E//c and E⊥c by using polarization-resolved PL. The energy separation between the polarization of E//c and E⊥c agreed exactly with the separation energy obtained by the normal PL. Therefore, two emission peaks with the energy separation of 40 meV are considered to originate from polarization of the strained AlGaN under tensile stress. Furthermore, we found that the energy separation of the polarization was increased linearly with the increase in Al mole fraction of the strained $Al_xGa_{1-x}N$ (x≤0.32). Such energy separation was not observed from the polarized PL of a 1-μm-thick $Al_xGa_{1-x}N$ (0≤x≤1) epilayers free from strain.[1] These results clearly demonstrate that energy separation in the polarization of $Al_xGa_{1-x}N$ due to biaxial strain was observed for the first time. **References** [1]K. B. Nam, J. Li, M. L. Nakarmi, J. Y. Lin, and H. X. Jiang, *Appl.Phys.Lett.* **84**, 5264 (2004) **Acknowledgements** This work was carried out in collaboration with High-Power, High-Frequency Gallium Nitride Device Project of NEDO, and also supported by the 21st Century COE Program of MEXT.

FF23.4

Structural and optical properties of MOCVD InAlN epilayers. S. Hernandez[1,2], D. Amabile[1], K. Wang[1], E. Nogales[1], D. Pastor[2], R. Cusco[2], L. Artus[2], R. W. Martin[1], K. P. O'Donnell[1], I. M. Watson[3] and Consortium the RENiBEl[1]; [1]Department of Physics, University of Strathclyde, Glasgow, Scotland, United Kingdom; [2]Institut Jaume Almera, CSIC, Barcelona, Barcelona, Spain; [3]Institute of Photonics, University of Strathclyde, Glasgow, Scotland, United Kingdom.

Nitride-based materials have generated a growing interest in the last few years because of their potential optoelectronic applications. $In_xAl_{1-x}N$ alloys can cover a very a wide range of energy since the band gap can be tuned from 6.1 to 0.6 eV by changing the relative cation concentration. In particular, $In_xAl_{1-x}N$ alloys lattice matched to GaN can provide, on the one hand, a large enough energy band gap to be used as an insulating barrier in GaN-based electronic devices, and, on the other hand, they can be used to fabricate strain-free structures on free standing GaN. However, the growth of these alloys is still difficult and they are relatively unexplored compared to other nitrides. Here we present an optical and structural study of $In_xAl_{1-x}N$ epilayers for InN compositions from 16 % to 24 %. The InN fraction was determined using wavelength dispersive x-ray analysis. The layers were grown by metal-organic chemical vapour deposition (MOCVD) on GaN templates and have a thickness of about 130 nm. The surface quality for the different compositions was analysed by scanning electron microscopy finding a flat and homogeneous surface for compositions near 18 % which, according to Vegard's law, is lattice matched to GaN. As the InN fraction is made to differ from the lattice matched value, the quality of the surface worsens, giving rise to an increasing density of surface structures such as small pits and crystallites. Photoluminescence excitation measurements were used to investigate the composition dependence of the band-gap, by monitoring the $^5D_0$-$^7F_2$ Eu-related emission in Eu implanted $In_xAl_{1-x}N$ epilayers. Raman scattering was used to study the vibrational properties of these layers. The Raman measurements were performed in backscattering configuration on the (0001) face. In this configuration, only the E_2 and the A_1(LO) modes are allowed. Besides the two Raman peaks corresponding to the E_2 (high) and A_1(LO) modes of the GaN substrate, three additional Raman peaks were observed in the frequency range between 500 and 900 cm^{-1}. We assign the two lower frequency additional peaks found in this region respectively to the InN-like and AlN-like E_2 (high) modes of the $In_xAl_{1-x}N$ epilayers, whereas the highest frequency peak is assigned to the A_1(LO) mode. The A_1(LO) mode shows a frequency blueshift for increasing AlN concentration. The observation in the Raman spectra of two E_2 (high) phonons and one A_1 (LO) mode is in good agreement with theoretical calculations that predict a two-mode behavior for the E_2 (high) phonons of the $In_xAl_{1-x}N$ alloy and a one-mode behavior for the A_1 (LO) phonons.

FF23.5

Optical waveguides of wurtzite Al1-xInxN/AlN/Sapphire structures prepared by plasma source molecular beam epitaxy technique. Yuriy Volodymyr Danylyuk, Ildar Salakhutdinov, Ivan Avrutsky and Gregory Auner; ECE SSIM, Wayne State University, Detroit, Michigan.

Al1-xInxN/AlN/Al2O3 films with (0 x 1) with different thicknesses were prepared by plasma source molecular beam epitaxy on c-plane sapphire substrates for optical waveguide study. The main obstacle for waveguide technique is that only coherent light sources could be used effectively for the determination of optical parameters. As a result, we can obtain only values of refractive indices for a discrete set of wavelength. A ZnSe prism and a fabricated grating coupler were employed to display waveguide modes (M lines) with wavelengths of 1553, 632.8, 532.1, 514.5, 488.0 and 377.0 nm. For comparison, the refractive index and thickness of the waveguide material were obtained separately by optical and ellipsometry reflectance measurements. Optical properties of the films were determined using fitting measured spectra of reflectance and transmittance by the Berning recurrent relations The results indicate an excellent agreement with experimental data. The relative rms errors for the real part of the index of refraction are close to 0.1%.

FF23.6

Surface Recombination and Vacuum/GaN/AlGaN Surface Quantum Wells. Xiyao Zhang[1], John Muth[1], John Roberts[2], Pradeep Rajagopal[2], Jim Cook[2], Eddie Piner[2] and Kevin Linthicum[2]; [1]ECE Dept, North Carolina State University, Raleigh, North Carolina; [2]Nitronex Corporation, Raleigh, North Carolina.

In III-Nitride devices thin Gallium Nitride capping layers have been used in a variety of ways, for example to improve a metal contact layer, or to modify the band structure shape for devices that depend on piezoelectric charge. With the correct material parameters and dimensions it is also possible to form a surface quantum well with the vacuum forming one interface, GaN the quantum well, and AlGaN forming the other interface. We have observed very efficient photoluminescence and cathodoluminescence from these structures without any special surface passivation. In this study we explore surface passivation strategies and their effect on surface quantum well emission.

FF23.7

Temperature Response of the Photoluminescence and Optical-Phonons in GaN and MgZnO Wide-Bandgap Films and Nanocrystallites. Jesse Huso[1], Xiang-Bai Chen[1], John L. Morrison[1], Heather Hoeck[1], Dario A. Machleidt[1], Frank Lamelas[1], Leah Bergman[1], Matthew D. McCluskey[2] and Andrew P. Purdy[3]; [1]Physics Department, University of Idaho, Moscow, Idaho; [2]Department of Physics, Washington State University, Pullman, Washington; [3]Chemistry Division, US Naval Research Laboratory, Washington DC, District of Columbia.

Understanding the properties of the wide-bandgaps at elevated temperatures and pressure is crucial to their applications as constituent materials in devices operating at extreme conditions. The nature of the photoluminescence (PL) emission of GaN film at temperature range of range of 77-900 K were studied. It was found that up to 280 K the emission is due to the free exciton and above this temperature a fast transition takes place in which the luminescence has a mixed exciton-bandgap characteristics, and at $\sim$ 400 K the emission is mainly due to bandgap recombination. The analysis indicted that the exciton binding energy in our GaN film is $\sim$ 24 meV. Additionally, the PL energy as a function of temperature was studied for both film and nanocrystallites. It was found that up to 600 K the PL energy of the nanocrystallites has similar characteristics to that of the film: a redshift of $\sim$ 155 meV was observed. Above that temperature the PL energy of the film exhibit a slower redshift trend relative to that of the crystallites. Moreover, the properties of the longitudinal optical phonons in GaN nanocrystallites were studied by temperature dependent Raman scattering and will be discussed in terms of crystal anharmonicities and thermal expansion. ZnO and MgZnO are promising emerging materials capable of luminescence in the ultraviolet (UV) spectral range. ZnO of the wurtzite structure has a bandgap of 3.37 eV while MgO of the cubic structure has a bandgap of 7.5 eV. Thus the MgZnO alloy system may provide a new optically tunable family of wide bandgap materials as well as a potential conjugate material in AlGaN-MgZnO hybrid devices. MgZnO nanocrystallites with an average size of $\sim$ 30 nm were synthesized via thermal decomposition at the University of Idaho. Samples having Mg concentrations of 0%, 7%, 13%, 26% were studied via photoluminescence, resonant-Raman scattering, TEM, XRD, and XPS. Our preliminary studies indicated that at these concentrations the crystallites still retain the hexagonal wurtzite structure. The nanocrystallites were found to exhibit room-temperature UV-photoluminescence for which the peak position depends on the Mg concentration: a blueshift of $\sim$ 0.3 eV was achieved as the Mg concentration increases from zero up to 26 percents. A discussion on the optical and structural properties of these novel alloy nanocrystallite system will be presented as well as their properties at elevated temperature and pressure. L B. gratefully acknowledges NSF CAREER DMR-0238845 and DOE-DE-FG02-04ER46142. L.B., F.L. and M.D.M. gratefully acknowledge American Chemical Society PRF 40749-AC10. A.P.P gratefully acknowledges the Office of Naval Research.

FF23.8

Cu induced optical transitions in MOCVD grown Cu doped GaN. Jayantha Senawiratne[1], Martin Strassburg[2,1], Nikolaus Dietz[1], Ali Asghar[2], Adam Payne[2], William E. Fenwick[2], Nola Li[2] and Ian T. Ferguson[2,3]; [1]Department of Physics and Astronomy, Georgia State University, Atlanta, Georgia; [2]Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, Georgia; [3]School of Materials Science and Engineering, Georgia Institute of Technology, Atlanta, Georgia.

Copper incorporated in GaN on lattice site acts as a double acceptor and has therefore attracted increased attention in the recent years. High-Ohmic material can be fabricated because of the deep level acceptor-like states introduced by Cu that compensates the residual donors (1). Using Coulomb pairing, Cu was used for co-doping purposes that have been applied to create shallow acceptor complexes (2). Furthermore, coppers electronic properties as a transition metal renders it as a candidate for spintronics materials. This work reports on the in-situ incorporation of Cu in metal organic chemical vapor deposition (MOCVD) grown GaN. For the first time, Cu related transitions in GaN were observed by photoluminescence (PL) that scale in their emission intensity with Cu doping concentration. The GaN:Cu thin films were grown on (0001) c- plane sapphire substrates using N,N'-Diisopropylacetamidinato copper (I) as copper source. The crystal quality of the deposited thin films was confirmed by XRD measurements. Different Cu concentrations in the GaN:Cu thin films were analyzed by secondary ion mass spectroscopy (SIMS) and were found to vary from 2x1016cm-3 to 5x1017 cm-3. Raman studies were performed with resonant and non-resonant excitation energies with respect to the Cu induced state. The prominent GaN Raman modes, A1(LO), E1(TO), E2(high), and A1(LO) were identified at 533, 560, 567, and 735 cm-1, respectively. The narrow linewidth (FWHM) of 5 cm-1 of the E2(high) mode confirms the high crystalline quality of Cu-doped GaN thin films, which is similar to that of MOCVD grown undoped GaN. No major peak broadening or peak shifting were detected as a result of Cu incorporation. The Cu related states were detected by both PL and absorption measurements. The PL studies revealed four major emission bands centered at 2.75 eV, 2.4 eV, 2.2 eV and 2.05 eV. The intensity of the green emission band (centered at 2.4 eV) appeared to strongly scale with respect to the Cu concentration. The electrical conductivity of the samples was analyzed by Hall measurements and indicates semi-insulating behavior. This semi-insulating behavior was attributed to the compensation of intrinsic donors by the deep Cu acceptor like states. (1) J. Senawiratne, M. Strassburg, and N. Dietz, A.M. Payne, A. Asghar, W.E. Fenwick, N. Li, and I.T. Ferguson, submitted to Applied Physics Letters (2005). (2) Z.C. Feng, A.M. Payne, D. Nicol, P.D. Helm, I. Ferguson, J. Senawiratne, M Strassburg, N. Dietz, Ch. Hums and A. Hoffmann, in "GaN and Related Alloys 2003", ed. H.M. Ng, M. Wraback, K. Hiramatsu, N. Grandjean; Mat. Res. Soc. Symp. Proc. 798, pp. 545-550 (2004).

FF23.9

Effect of passivation on photoluminescence of GaN. Serguei Chevtchenko[1], Kaigui Zhu[1], Yong-Tae Moon[1], Mikhail A Reshchikov[2] and Hadis Morkoc[1]; [1]Electrical Engineering Department, VCU, Richmond, Virginia; [2]Department of Physics, VCU, Richmond, Virginia.

We investigated the influence of passivation on optical properties and surface band bending in unintentionally doped GaN studied by steady-state photoluminescence (PL) and surface potential electric force microscopy (SP-EFM). The GaN samples under study were grown by metal-organic chemical-vapor deposition on c-plane sapphire substrate and had carrier concentration of about 10^{17} cm^{-3} as determined from the Hall effect measurements. After reducing the natural oxide by chemical etching in acid solution HNO_3:HCl, the deposition of SiO_2 and SiN_x films was performed by chemical vapor deposition at 300^oC by using SiH_4, He, and O_2 or N_2, respectively. The thickness of the deposited films was about 10nm. All further studies were performed on untreated (control) and passivated samples. PL measurements were carried out at room temperature using a continuous wave He-Cd laser (325nm). For both types of passivation we observed a significant increase of PL intensity in the near-band-edge region. In the case of SiO_2, the PL intensity increased by a factor of 6.5, and for SiN_x film by a factor of 3.5. Surface potential EFM measurements were performed utilizing Au-coated cantilever and were calibrated to the value of potential for Au-covered plate. The measured surface potential was the same for control and passivated samples within the experimental error. The value of the surface band-bending was determined as 1.0 ± 0.2 eV in both cases. We suggest that the strong enhancement of PL is caused by reduction of contribution of the surface states to recombination of photogenerated carriers after passivation. An alternative, widely accepted explanation that the PL intensity increases due to decreasing band banding at the surface, contradicts to our observations of unchanged band bending from the SP-EFM study. We assume that the effective density of the surface states responsible for the surface band bending remains unchanged upon passivation, whereas the total density of the surface states is significantly reduced. It is possible also that the band bending is saturated in our case, and marked reduction of the surface state density does not effect the band bending.

FF23.10

Refractive Indices of A-plane GaN Thin Films on R-plane Sapphire. Ailing Cai[1], John Muth[1], Andrei Osinsky[2], J. Q. Xie[2], Amir Dabiran[2], C. Mueller[3] and S. Alterovitz[4]; [1]ECE Dept, North Carolina State University, Raleigh, North Carolina; [2]SVT Associates, Eden Prairie, Minnesota; [3]Analex Corporation, Cleveland, Ohio; [4]NASA Glenn Research Center, Cleveland, Ohio.

Epitaxial a-plane GaN thin films grown on r-plane sapphire are promising materials for optoelectronic applications such as laser diodes and LEDs. The absence of a built-in electrostatic field in the nonpolar a-plane GaN-based quantum wells can limit the piezoelectric polarization effect and result in higher emission efficiency. However, the anisotropic optical properties a-plane GaN are important to understand and are fundamental for optoelectronic devices design. In this study, two a-plan GaN samples were investigated with imaging cathodoluminescence, atomic force microscopy and prism coupling measurement. One sample was on r-plane sapphire, the other was on miscut r-plane sapphire. Triangular shaped pits and a network of dislocations associated with the pits were observed for the thicker sample grown on the r-plane sapphire. On the thinner sample grown on miscut r-plane sapphire the morphology was smooth and dislocations were not observed in imaging cathodoluminescence, however waveguiding measurements revealed a significant tilt of the optical axis which complicates the propagation of light in waveguides devices. Thus for successful optoelectronic device design for a-plane GaN devices on miscut r-plane sapphire the orientation of the device on the wafer becomes important since the refractive index becomes a function of azimuthal angle for both TE and TM polarized light.

FF23.11
High quantum efficiency of photoluminescence in GaN and ZnO. Michael A. Reshchikov[1], Xing Gu[2], Jeff Nause[3] and Hadis Morkoc[2,1]; [1]Dept. of Physics, VCU, Richmond, Virginia; [2]Dept. of EE, VCU, Richmond, Virginia; [3]Cermet, Inc., Atlanta, Georgia.

The performance of opto-electronic devices, especially those operating in the visible and ultraviolet ranges of the optical spectrum depends on the quantum efficiency (QE) of emission in general and photoluminescence (PL) in particular. Qualitative terms such as "very intense PL that confirms high-quality of the material" are omnipresent in the literature. However, there have been very few attempts to estimate the absolute value of PL intensity or its QE. We estimated the external QE of PL from GaN and ZnO state-of-the-art crystals by direct measurement of the PL power with corrections for the geometry of PL registration optics and refraction inside the crystal. The internal QE of PL has been estimated by an indirect method based on competition of radiative and nonradiative recombination channels [1]. A Si-doped GaN sample grown by molecular beam epitaxy exhibited the highest internal QE, exceeding 80%. Recombination via the shallow donor-acceptor pair transitions dominated in our Si-doped GaN layers, and the concentration of the shallow acceptor reached mid 10^{17} cm^{-3} in these samples, as estimated from analysis of steady-state and time-resolved PL. In contrast, a bulk ZnO crystal with the PL internal QE of about 60% contained almost no defect- or impurity-related PL signatures besides the emission attributed to free and bound excitons. The sources of radiative and nonradiative recombination in GaN and ZnO will be discussed. [1] M. A. Reshchikov and R. Y. Korotkov, Phys. Rev. B 64, 115205 (2001).

FF23.12
Photoluminescence in carbon-doped wurtzite GaN.
Michael A. Reshchikov, Dept. of Physics, Virginia Commonwealth University, Richmond, Virginia.

While carbon in cubic GaN introduces a shallow acceptor level that is responsible for reliable p-type conductivity [1], its role in wurtzite GaN is not well established to date [2]. There are many reports that C-doping greatly enhances the yellow luminescence (YL) band and therefore it is involved in the defect responsible for this band. Others expect that C introduces a shallow acceptor that is responsible for the shallow donor-acceptor pair (DAP) band in unintentionally doped GaN. Finally, first-principle calculations predict [3] that C_N indeed has the lowest formation energy in n-type GaN, especially when Ga-rich conditions of growth are employed, and therefore it can be responsible for the shallow DAP band in GaN. We studied photoluminescence (PL) from a set of GaN layers grown on sapphire substrate by metalorganic chemical vapor deposition and doped with different amount of carbon. One of the remarkable features in these samples is extremely low intensity of the shallow DAP band. Analysis of the PL data gives the shallow acceptor concentration of about 10^{14} cm^{-3} in most of the C-doped GaN layers. This result shows that C does not form a shallow acceptor C_N in appreciable concentrations in wurtzite GaN. As for the YL band, there is no clear correlation between its intensity and degree of C-doping. The question of whether the YL in undoped and C-doped GaN is caused by the same or different defects [4] deserves careful attention and will be analyzed in this work. [1] D. J. As, D. G. Pacheco-Salazar., S. Potthast, and K. Lischka, Mater. Res. Soc. Symp. Proc. 798, Y8.2 (2004). [2] M. A. Reshchikov and H. Morkoc, J. Appl. Phys. 97, 061301 (2005). [3] A. F. Wright, J. Appl. Phys. 92, 2575 (2002). [4] R. Armitage, W. Hong, Q. Yang, H. Feick, J. Gebauer, E. R. Weber, S. Hautakangas, and K. Saarinen, Appl. Phys. Lett. 82, 3457 (2003).

FF23.13
Characterisation of the optical properties of Tm doped and ion implanted GaN. Iman S Roqan[1], Emilo Nogales[1], Carol Trager-Cowan[1], Kevin P O'Donnell[1], Robert W Martin[1], Katharina Lorenz[2], Eduardo Alves[2], Olivier Briot[3] and Georgios Halambalakis[3]; [1]Physics Department, University of Strathclyde, Glasgow, United Kingdom; [2]ITN, Sacavem, Portugal; [3]Groupe dEtudes des Semiconducteurs, University of Monpellier II, Montpellier, France.

Rare earth (RE)-activated GaN (GaN:RE) has recently sparked considerable interest because of the combination of GaN with the optical emission of RE species which could lead to many important photonic applications. Comparative studies of the cathodoluminescence (CL) properties of in situ doped MBE GaN:Tm and Tm implanted GaN films have been carried out. Wavelength dispersive X-ray spectroscopy (WDX) and room temperature CL mappings were performed in an electron probe microanalyser to measure optical emission, elemental compositions and RE concentrations in the films. The results of temperature dependence and time-resolved luminescence will be reported for both blue (477 nm) and infrared (805 nm) emissions which are due to intra $4f^n$-shell electron ($^1G_4$ to $^3H_6$) and ($^3H_4$ to $^3H_6$) transitions associated with Tm^{3+} ions. We will discussed the energy transfer mechanism from the host to Tm^{3+} ions in both MBE and implanted GaN:Tm. In addition, the influence of growth temperature on Tm concentration and optical properties of MBE GaN:Tm will be discussed.

FF23.14
Correlation Between Resistivity and Yellow Luminescence Intensity of MOCVD-Grown GaN Layers. Akihiro Hinoki[1], Yuichi Hiroyama[3], Tadayoshi Tsuchiya[3], Tomoyuki Yamada[3], Masayuki Iwami[3], Katsuhiro Imada[3], Junjiroh Kikawa[3], Tsutomu Araki[1], Akira Suzuki[2,3] and Yasushi Nanishi[1]; [1]Dept. of Photonics, Ritsumeikan Univ., Kusatsu, Shiga, Japan; [2]Res. Org. of Sci & Eng., Ritsumeikan University, Kusatsu, Shiga, Japan; [3]Advanced HF Device R&D Center, R&D Association for Future Electron Devices, Kusatsu, Shiga, Japan.

GaN and related alloys have attractive physical properties such as high saturation velocity, high breakdown electric field and good thermal conductivity. Owing to these inherent material properties, AlGaN/GaN HFETs have been extensively studied as promising electronic devices for high-speed, high-power and high-temperature operation. For further improvements in device performance, however, there are still several issues to be solved. For example, reduction in leakage current through the Schottky barrier gate and suppression of current collapse are required to increase the power density. Moreover, the reduction in drain-source leakage current is also important for higher power operation. To reduce the drain-source leakage current, high-resistivity GaN epi-layer is necessary. Usually, the resistivity of a GaN epi-layer is measured by an I-V measurement after metal contact processes. Previously, we have found that luminescence image of 2-inch GaN epi-layers taken by UV lamp excitation is a useful way to evaluate uniformity of the epi-layers [1]. In this work, we report on correlation between the resistivity and the luminescence intensity of the GaN epi-layers. Unintentionally-doped 2 μm GaN epi-layers with different resistivity were grown by MOCVD on sapphire and SiC substrates. AlGaN/GaN HFET structures grown by MOCVD on the sapphire substrate were also used. When the samples were excited by a UV lamp, grossly-visible yellow luminescence (YL) was observed. The luminescence images were recorded by taking a picture of the GaN epi-layer. The wavelength and the power density of the UV light are 365 nm and 100 $\mu W/cm^2$, respectively. The resistivity of the samples was measured by a contactless measurement using COREMA. The current-voltage (I-V) characteristics were measured using a 4155A semiconductor parameter analyzer. The luminescence image and COREMA results showed that the YL intensity clearly increases with the decrease in the sheet resistance of the GaN epi-layers. We recognized clear correlation between the leakage current of the I-V characteristics and the YL intensity for the 3 inch GaN epi-layer. The in-plane distribution of the leakage current also well corresponded to the in-plane distribution of YL intensity, indicating that the region showing strong YL has large leakage current. The similar correlation between the leakage current and the YL intensity was also observed for the AlGaN/GaN HFET samples. These results confirmed that the leakage characteristics of AlGaN/GaN HFET samples could be simply evaluated by measuring the YL intensity. The origin of the YL of GaN epi-layers associated with their leakage characteristics is under consideration. [1] Hiroyama et al., Extended Abstracts (The 65th Autumn Meeting, 2004) JSAP, 312 (2004). Acknowledgements This work was carried out in collaboration with High-Power, High-Frequency Gallium Nitride Device Project of NEDO, and also supported by the 21st Century COE Program of MEXT.

FF23.15
Influence of the annealing ambient on structural and optical

properties of Er implanted GaN. Katharina Lorenz[1,2], E. Nogales[3], R. Nedelec[4], J. Penner[4], R. Vianden[4], E. Alves[1,2], R. W. Martin[3] and K. P. O'Donnell[3]; [1]Departamento de Fisica, Instituto Tecnologico e Nuclear, Sacavem, Portugal; [2]CFNUL, Lisbon, Portugal; [3]Department of Physics, University of Strathclyde, Glasgow, United Kingdom; [4]HISKP, University of Bonn, Bonn, Germany.

Doping of GaN with optically active rare earth elements (RE) allows the production of electroluminescent emitters that cover the entire visible wavelength range. Ion implantation is a powerful technique to introduce rare earth ions in a reproducible way with a defined depth and concentration profile. However, this method still suffers from the incomplete annealing of the resultant lattice damage even at high temperatures. In this work we study structural and optical properties of GaN doped with Er by ion implantation followed by thermal annealing in different atmospheres. The recovery of the lattice was analysed after rapid thermal annealing at 1000 and 1100 °C in vacuum, flowing nitrogen gas or a mixture of NH_3 and N_2. Rutherford backscattering spectrometry in the channeling mode (RBS/C) was used to study the evolution of damage introduction and recovery in the Ga sublattice and to monitor the change of the Er profile after annealing. The surface morphology of the samples was analysed by SEM and the optical properties by room temperature cathodoluminescence (CL). While samples annealed in vacuum and N_2 already show first signs of surface dissociation at 1000 °C and a strong loss of GaN and Er for higher temperatures, the samples annealed in NH_3 plus N_2 exhibit a good recovery of the lattice along with a smooth surface for the highest temperature. These samples also show the strongest CL intensity with emissions in the green at 538.5 and 558.5 nm.

FF23.16
Electrical Conductivity Measurements of Sputter-Deposited Scandium Nitride Thin Films. Mark E Little[1], Matt E. Koepke[2] and Andrew Moore[1]; [1]Physics and Engineering, Hope College, Holland, Michigan; [2]Physics, West Virginia University, Morgantown, West Virginia.

The electrical and optical properties of sputter-deposited ScN films on sapphire have been investigated using Hall Effectt and optical absorption techniques. Film growth temperature was varied from room temperature to 800 °C. Sheet resistance is seen to decrease exponentially with increasing growth temperature from $5x10^{-11}$ to 12000 Ω/. Sheet carrier density was observed to increase exponentially while mobility remained relatively constant (~ 2 $cm^2/V \cdot s$) for growth temperatures above 400 °C. Absorption measurements show an average band gap of 2.8 eV with some samples having a distinct increase in adsorption at ~4.6 eV. Currently, film composition and structure are being analyzed by RBS and XRD to help determine the nature of the electrical and optical measurements. The results of both investigations will be presented.

SESSION FF24: Poster Session: Dopants/Defects
Chairs: Leah Bergman and Nicolas Grandjean
Thursday Evening, December 1, 2005
8:00 PM
Exhibition Hall D (Hynes)

FF24.1
Donor-like Deep Level Defects in GaN Characterized by Double-correlation Deep Level Transient Spectroscopy. Mo Ahoujja[1], M. Hogsed[2], Y. K. Yeo[2] and R. L. Hengehold[2]; [1]Physics, University of Dayton, Dayton, Ohio; [2]Engineering Physics, Air Force Institute of Technology, Wright-Patterson AFB, Ohio.

Si doped GaN samples grown by radio-frequency plasma activated molecular beam epitaxy on sapphire substrates were characterized by capacitance transient spectroscopy. Conventional deep level transient spectroscopy (DLTS) measurements show 6 deep level defects, labeled A1, A, B, C1, C, and D, with activation energy ranging from 0.20 to 0.82 eV below the conduction band, in agreement with the literature. Based on the logarithmic dependence of the DLTS spectral peaks on the filling pulse width, it is deduced that most of these traps are concentrated in the vicinity of line dislocations. Double-correlation DLTS (DDLTS) measurements were subsequently used to provide information on whether any of these deep levels exhibits donor-like characteristics. It is found that only defects A (0.82 eV) and D (0.22 eV) display a strong electric field dependence. This so-called Poole-Frenkel behavior indicates that these 2 defects are deep donors. Following 1.0 MeV electron irradiation of the GaN sample, DLTS spectra show one radiation-induced peak, E, with activation energy less than 0.20 eV. It is noteworthy that the other peaks seen in the as-grown sample remain largely unaffected by irradiation. The DLTS signal of trap E is rather broad and is a combination of traps ER1 and ER2 reported in the literature. Furthermore, the DLTS peak intensity of trap E was found to diminish significantly after annealing at 350 oC

FF24.2
Abstract Withdrawn

FF24.3
Thin Capping Layers For Protection During High Temperature Annealing Of Rare Earth Implanted GaN. Emilio Nogales[1], Katharina Lorenz[2], Robert W. Martin[1], Iman S. Roqan[1], Kevin P. O'Donnell[1], Eduardo Alves[2], Sandra Ruffenach[3] and Olivier Briot[3]; [1]Department of Physics, University of Strathclyde, Glasgow G4 0NG, United Kingdom; [2]ITN, Estrada Nacional 10, 2686-953 Sacavem, Portugal; [3]GES, Universite de Montpellier II, 34095 Montpellier, France.

The structure of several AlN caps grown on GaN by MOCVD has been studied with scanning electron and atomic force microscopies in order to assess its influence on the protection against the GaN dissociation that arises during annealing treatments at temperatures in excess of 1100oC after rare earth implantation. The AlN gives good protection up to at least 1300oC except for the formation of surface holes, with sizes in the micron range, that degrade the properties of the samples. Crack formation has been observed in as-grown AlN caps thicker than the critical thickness and has been found to be the main factor leading to the formation of the holes, due to local dissociation of GaN through them. Room temperature cathodoluminescence (CL) and wavelength dispersive X-ray microanalysis (WDX) mappings have been simultaneously obtained in an electron probe microanalyser from rare earth implanted, high temperature annealed samples to study with high spatial resolution the correlation between the emission properties and the composition in the defects. The rare earth related CL emission from the boundaries of the holes shows differences with respect to the one from the surface not affected by decomposition. Low and room temperature photoluminescence studies have been carried out to compare the rare earth emission from samples with different surface densities of holes. Several ways to overcome the degradation of the samples have been tried, using either a different structure as capping layer or several techniques to protect the AlN cap during the annealing. Some of these methods have been shown to be successful, allowing annealing temperatures in excess of 1300oC without degradation of the samples. Thus, it has been possible to study the emission properties after annealing temperatures at which the removal of implantation damage is complete.

FF24.4
Characterization of Electron Traps in n-Type GaN Layers Grown by MOCVD on Bulk GaN Substrates. Yutaka Tokuda[1], Wakana Nakamura[1], Youichi Matsuoka[1], Hiroyuki Ueda[2], Osamu Fujishima[2] and Tetsu Kachi[2]; [1]Department of Electrical and Electronics Engineering, Aichi Institute of Technology, Toyota, Japan; [2]Toyota Central Research and Development Laboratories, Inc., Nagakute, Japan.

It is desirable to use GaN layers grown homoepitaxially on bulk GaN substrates for fabrication of various devises due to the reduction of dislocation density. Moreover, it enables us to fabricate the vertical device structures, which is useful for the high power device application. In this work, we characterize electron traps in n-type GaN layers grown by MOCVD on free-standing GaN substrates. Deep-level transient spectroscopy (DLTS) was applied to the vertical Schottky diodes fabricated on MOCVD-grown layers with the ohmic contacts on the bulk surface of GaN substrates. The DLTS results for the vertical Schottky diodes were compared with those for the lateral ones on MOCVD layers on sapphire substrates. Free standing GaN grown by HVPE was used as a substrate for the GaN layer grown by MOCVD. The thickness of the MOCVD layer was 5μm. Pt/Au and Ti/Al contacts were formed as a Schottky contact on the MOCVD layer and an ohmic contact on the back side of the substrate, respectively. The diameter of the Schottky contact was 0.5 mm. DLTS measurements were carried out in the temperature range from 80 to 600 K. One dominant trap with the energy level of Ec - 0.56 eV was observed in the MOCVD GaN layer on the bulk GaN substrate with the minor trap with the energy level of Ec - 0.22 eV. These traps were also observed in the MOCVD layer on the sapphire substrate, which contains three additional traps. The fewer traps in the MOCVD layer on the bulk substrate might be correlated to the expected reduction in dislocation density. However, one order of magnitude variation in concentration of the Ec - 0.56 eV trap was found in the area 10 mm x 10 mm of the MOCVD layer on the bulk substrate. This result will be discussed in connection with the Schottky diode characteristics.

FF24.5
Migration and Interactions of N Interstitials in p-Type GaN. Ryan R. Wixom and Alan F. Wright; Sandia National Laboratories, Albuquerque, New Mexico.

Under equilibrium conditions, one would not expect the formation of

a large concentration of N interstitials in GaN, since calculated formation energies are prohibitively high. However, it isn't perfectly clear how well this reasoning corresponds to the non-equilibrium high temperature process of organometallic vapor phase epitaxy (OMVPE). In any case, it is not surprising that large numbers of N interstitials will result from irradiation or ion-implantation. A recent study on the interactions of point-defects in proton irradiated material suggests that N interstitials become mobile during subsequent anneals and bind to MgH centers. Using density functional theory, we have investigated migration of the N interstitial and the formation of complexes with Mg and MgH. We will discuss our results in light of recent experiments.

FF24.6
SiH_4 exposure of GaN surfaces: A useful tool for highlighting dislocations. Rachel A. Oliver, Menno J. Kappers, Joy Sumner, Ranjan Datta and Colin J. Humphreys; Department of Materials Science and Metallurgy, University of Cambridge, Cambridge, United Kingdom.

Reducing the dislocation density in GaN epilayers grown on sapphire is vital to the improvement of LED performance, particularly for emission in the near UV. Hence, fast-turnaround, accurate methods for the assessment of dislocation densities are an essential research tool. Here, we present an *insitu* surface treatment in which GaN is exposed to fluxes of SiH_4 and NH_3 at 860 °C. GaN surfaces exhibit evenly-spaced monolayer steps, some of which terminate at a dislocation of screw or mixed character, where a small pit may be observed. Following a 240 s exposure to SiH_4 and NH_3, these pits were found to have more than doubled in diameter, as measured by atomic force microscopy (AFM). Additional small pits had appeared, not associated with step-edge terminations, which are believed to relate to edge-type dislocations. The total density of pits on the treated surface corresponded to the total dislocation density measured by transmission electron microscopy (TEM). Pits related to edge dislocations are often overlooked in AFM of untreated GaN. As the SiH_4 treatment time is increased, the measured dislocation density initially increases, but a 240 s treatment is sufficient to highlight all the dislocations. The pit width initially increases with treatment time, but then plateaus. If the SiH_4 were etching the dislocation pits, we might expect the increase in pit size with time to continue. Hence, other mechanisms for pit size increase are being considered. The SiH_4 treatment is effective in increasing dislocation pit size on both n- and p-type material, and has also been used on partially coalesced GaN layers. Following growth and annealing of the GaN nucleation layer on sapphire, the epilayer is grown at low V:III ratio to give slow coalescence. A mixture of large (1 - 2 μm high) and small ($\sim$200 nm high) islands are observed by AFM. Material grows on the tops of the larger structures in stacks of monolayer-high, two-dimensional (2D) islands, concentric about the island centre. It was suggested that the 2D islands nucleate on threading edge dislocations. Highlighting the dislocations using SiH_4, we find no threading edge dislocations at the island centre. We are able to observe pits associated with dislocations terminating on the large islands' facets, consistent with cross-sectional transmission electron microscopy (TEM) observations. The coalescence of islands is expected to lead to the formation of low-angle grain boundaries, giving rise to lines of threading edge dislocations. However, in AFM examination of coalescence boundaries for a sample in the early stages of coalescence this is very rarely observed. Lastly, we see that the smaller islands contain a much higher density of threading dislocations than the larger structures (as has been confirmed by TEM) and propose that a potential route to reducing the dislocation densities in GaN epilayers on sapphire, may be to anneal the film to desorb these smaller islands, prior to full film coalescence.

SESSION FF25: Poster Session: Heterostructures
Chairs: Leah Bergman and Nicolas Grandjean
Thursday Evening, December 1, 2005
8:00 PM
Exhibition Hall D (Hynes)

FF25.1
Strain Relaxation in Indium-rich InGaN/GaN Quantum Well Structures. Pedro M. F. J. Costa, Ranjan Datta, Menno Kappers and Colin Humphreys; Materials Science, University of Cambridge, Cambridge, United Kingdom.

Theoretical calculations of green light-emitting InGaN/GaN multiple quantum well (MQW) structures have shown it is possible to reduce the radiative lifetime by decreasing the InGaN well width while maintaining a fixed emission wavelength with a concurrent increase in the indium fraction. The more effective competition that the shorter radiative carrier recombination times can provide against the non-radiative recombination processes should lead to an improvement of the quantum efficiency. However, the misfit strain between the pseudomorphically grown InGaN and GaN layers would exceed 2% when the indium content of the quantum wells is raised beyond 20%. In many other semiconductor systems this level of strain results in the nucleation of misfit dislocations which, in turn, may act as non-radiative recombination centres reducing the devices efficiency. It is therefore of paramount importance to study indium-rich InGaN/GaN MQW structures for strain-relaxation phenomena as a function of the alloy composition and the number of quantum wells used. A series of blue and green InGaN/GaN QW structures with the number of wells varying from 1 to 10 were grown on a Thomas Swan 6x2 MOVPE reactor. Two types of QW growth conditions have been used; the so-called single-temperature structures for which the well and barrier growth temperatures were kept constant with Twell= Tbarrier <730 C and the two-temperature structures for which the temperature was varied for the well and barrier growth, with Twell<730 C and Tbarrier=860 or 900 C. The analysis by transmission electron microscopy (TEM) techniques of the blue InxGa1-xN/GaN 10 QW structures with x=0.16 show quantum well layers with uniform thicknesses and free of misfit dislocations. However, with increased indium-content to x>0.20 in the green MQW structures the analysis clearly shows the widespread presence of dislocations generated in the QW stack and the generation of inhomogeneities in the well thicknesses. The strain-related dislocations would be invisible under commonly used TEM diffraction conditions but are evident in weak-beam dark-field TEM with g= <11-20>. The misfit dislocations are seen to originate in the basal plane of the InGaN/GaN interfaces but bend over abruptly into the growth direction, effectively forming edge-type threading dislocations (TD). Few misfit-TDs were observed in indium-rich single QW structures but the number of dislocations seems to multiply beyond the second quantum well suggesting a greater strain relaxation with the number of QWs grown. In this contribution we present extensive TEM evidence for the presence of misfit TD in the indium-rich InGaN/GaN QW stacks and discuss the possible mechanisms of their formation.

FF25.2
Comparative investigation of quantum-dot-like localization centers in InGaN quantum well and quantum dot structures. K. Sebald, R. Kroeger, H. Lohmeyer, J. Gutowski, T. Yamaguchi and D. Hommel; Institute of Solid State Physics, University of Bremen, Bremen, Germany.

It is still subject of discussion if inhomogeneous distributions of In in InGaN quantum well (QW) samples act as quantum-dot-like (QD) localization centers, and if these centers are responsible for the device related optical properties of InGaN based structures. To fully utilize their potential for future device applications the optical properties of single strongly localizing centers must be thoroughly studied. We report on comparative micro-photoluminescence (μ-PL) studies on strong-localization centers in InGaN QW and QD structures. The samples were grown by MOVPE. One sample consists of an InGaN QW with a thickness of $\sim$5 nm which has been deposited on a GaN buffer layer at T=820°C and atmospheric pressure. The InGaN was overgrown at T=700°C by a GaN capping layer. The other kind of samples consists of InGaN layers deposited at T=700°C for which formation of QD structures is expected. The samples were overgrown by an InGaN layer, respectively. The optical investigations are carried out by using a temperature variable μ-PL setup. The samples are excited nonresonantly at 3.82 eV. At T=4 K the μ-PL spectra exhibit, besides a broad-band emission, spectrally well separated sharp emission lines. Their optical properties can be investigated even on an unstructured sample. The emission peaks possess linewidths down to 0.2 meV which is in the order of the spectral resolution of the experimental setup. With increasing excitation density the energy positions of these lines remain constant in contrast to the emission originating from a QW which blue-shifts as a result of state filling effects. The experimental findings are known for complexes possessing a δ-function-like density of states and carriers confined in strongly localizing potentials. Additionally, for the QW sample emission lines originating from biexcitonic complexes are detected, yielding binding and antibinding energies of about +5 meV and -5 meV, respectively. The observation of multi-exciton states and especially the finding of antibinding complexes, which can only be stable in QD-like structures due to the localizing confinement potential, confirm the assumption that the strong localization centers observed here act as QD-like structures. Furthermore μ-PL measurements of the single emission lines in dependence on the temperature are carried out to analyze special properties of the different emission centers. To gain insight into the structural origin of the sharp emissions lines and to confirm their QD nature, we established a technique to perform μ-PL and transmission electron microscopy (TEM) on exactly the same spatial spot regions of the samples. For this purpose, the samples are structured by focused-ion-beam etching into mesas with diameters of several 100 nm. After scanning the samples by μ-PL for areas of particular interest, TEM lamellas were prepared with regard to these spots, and the morphological structure has been investigated. The findings will be comparatively discussed.

FF25.3
AlGaN and AlInN based Quantum Wells for UV Emitters.
Eric Feltin, Jean-Francois Carlin, Sylvain Nicolay, Raphael Butte, Nicolas Grandjean and Marc Ilegems; FSB/IPEQ/LASPE, EPFL, Lausanne, Switzerland.

The fabrication of UV emitters has recently attracted much attention due to their potential applications in solid state lighting and biology. The commonly used active material system for UV to deep-UV emitters is $Al_xGa_{1-x}N/Al_yIn_zGa_{1-y-z}N$ with high aluminum content AlGaN barriers to minimize absorption issues occurring at short wavelengths. For such structures, a tensile strain originating from the difference between the lattice parameters of GaN and $Al_xGa_{1-x}N$ alloys (up to 2.5% for x=1) appears. This built-in strain is a key issue for device fabrication as it generally leads to the formation of dislocations and/or cracks with densities increasing with the aluminum content. To overcome cracking, AlN is usually used instead of GaN as a template leading to even higher dislocation densities ($> 10^{10}$ cm^{-2}). An alternative approach consists in using $Al_{0.82}In_{0.18}N$ layers lattice-matched to GaN while providing low absorption. In this work we report on the growth of $GaN/Al_xGa_{1-x}N$ and $GaN/Al_yIn_{1-y}N$ quantum wells (QWs) covering the 320-380 nm range. These QWs were grown on thick $Al_xGa_{1-x}N$ or $Al_yIn_{1-y}N$ layers deposited on standard GaN templates on 2 inch c-plane sapphire substrates by metalorganic vapor phase epitaxy. The dislocation density, a particularly important parameter for nitride based devices, was kept below 10^9 cm^{-2} by maintaining the lattice mismatch between the barrier and the well materials under 1%. Despite this reduced lattice mismatch to GaN, $Al_{0.3}Ga_{0.7}N$ and $Al_{0.9}In_{0.1}N$ layers layers are subject to cracking during the growth. However, the appearance of cracks was successfully avoided by applying a compressive strain by inserting a thin AlN/GaN superlattice before the growth of these QWs. Optical characterizations of AlInN and AlGaN based QWs were done by photoluminescence and reflectivity measurements. Narrow emission linewidths ranging from 12 meV to 60 meV (at 10K) in the 380-320 nm range were obtained after growth optimization. These linewidths are explained by a high homogeneity of the $Al_xGa_{1-x}N$ and $Al_yIn_{1-y}N$ layers and by smooth interfaces as evidenced by cathodoluminescence, atomic force microscopy and transmission electron microscopy. Particular issues such as surface morphology, internal absorption, and strain management for the fabrication of AlInN and AlGaN based MQWs will be also discussed.

FF25.4
An Integrating View on the Structural and Optical Properties of InGaN Semiconductor Alloys.
Sergio Pereira[1,2], Rosario Correia[1], Eduardo Alves[2], Kevin O'Donnell[3] and Ian Watson[4]; [1]University of Aveiro, Aveiro, Portugal; [2]ITN, Lisbon, Portugal; [3]Physics, University of Strathclyde, Glasgow, United Kingdom; [4]Institute of Photonics, Glasgow, United Kingdom.

Energy efficient and environment friendly solid-state-based light sources are revolutionizing an increasing number of applications and can result in tremendous benefits in vast areas such as lightning, automobiles, communication, imaging and medicine. These major technological advances would not have been possible without the spectacular devolvement in group III-nitride semiconductors, and in particular in indium gallium nitride (InxGa1-xN) alloys. The high quantum emission efficiency obtained in InGaN based light emitting diodes (LEDs) and laser diodes (LDs) with high density of defects and poor crystalline quality, is by several means remarkable. After intensive research efforts in the last decade the InGaN alloy is still very poorly understood material system. In this contribution we present the results of an experimental work performed on a large number of InGaN samples grown by metal organic chemical vapour deposition (MOCVD) in several laboratories around the world. The fundamental purpose of this study is to provide grounds for better understanding of the yet unclear physics of this important material system, and help to fill the gap between basic scientific knowledge and technological applications. The approach taken is to integrate information provided by several complementary structural and optical characterization techniques through a systematic and multidisciplinary analysis. Specifically we combine: 1) sample growth by MOCVD with specific features in an attempt to isolate the influence of structural parameters, such as layer thickness and composition; 2) Advanced structural characterization by atomic force microscopy (AFM), scanning electron microscopy (SEM), X-ray diffraction (XRD) and Rutherford Backscattering spectrometry (RBS); 3) Optical characterisation at complementary length scales by: optical absorption (OA), photoluminescence (PL), Raman and cathodoluminescence (CL) spectroscopy and confocal microscopy (CM) spectroscopy. The results obtained allow an integrated perspective of the structural and optical properties and the importance of knowing the critical layer thickness (CLT) for strain relaxation and 3D growth, for a given composition, is clearly evidenced. Additionally, by growing samples below and above the CLT, the appearance of the 3D island-related relaxed regions in the XRD reciprocal space map RSM could be closely monitored. A subsequent surface etching, on samples grown above the CLT, evidences that the relaxed component disappears, and therefore a direct correlation between the onset of 3D islanding growth, strain relaxation and the observation of double PL and XRD peaks in InGaN could be established for the first time. Simple interpretation models to describe the nano-structural and optical features are proposed. This study also provides an insight on why InGaN alloys are generally believed to be phase segregated for compositions above ~0.06.

SESSION FF26: Poster Session: Structural
Chairs: Leah Bergman and Nicolas Grandjean
Thursday Evening, December 1, 2005
8:00 PM
Exhibition Hall D (Hynes)

FF26.1
Stresses experienced by AlN films grown on sapphire.
Jie Bai and Michael Dudley; SUNY, Stony Brook, Stony Brook, New York.

AlN has attracted extensive research attention due to its intrinsic properties and its low lattice mismatch with GaN. However, with cracking being one of the problems of AlN epitaxy, stresses experienced by AlN film during and after growth requires investigation. There are three predominant factors which contribute to the stress experienced by the film: tensile stress due to the coalescence of the islands at the initial growth stage (refer as coalescence stress); residual mismatch stress due to the incomplete relief of the lattice mismatch between the substrate and the film (refer as residual mismatch stress); extrinsic stress introduced by the cooling-down process (refer as cooling down stress). In this paper, two AlN/sapphire samples with one under tension and the other one under compression are studied and compared. In this study, coalescence stress is calculated with the 3D-island sizes being measured by AFM. Residual mismatch stress is precisely calculated based on the measurement of plastically accommodated lattice mismatch by HRTEM. Along with the calculated cooling down stress, the stress experienced by these two AlN epi-films can be acquired. A general discussion of the aforementioned stresses in AlN epitaxy will also be presented.

FF26.2
A TEM Investigation of the Role of an Ultrathin AlN Capping Layer during the RE Implantation of GaN for Electroluminescence Applications.
Ruterana Pierre[1], Florence Gloux[1], Tomasz Wojtowicz[1], Katharina Lorennz[2] and Eduardo Alves[2]; [1]SIFCOM, ENSICAEN, Caen, France; [2]ITN, Sacavem, Portugal.

Ion implantation is an efficient and versatile method that is used in the semiconductor industry for doping in devices, we are now investigating its application to for Rare Earth (RE) atoms incorporation in GaN. It contributes to creation of a considerable amount of structural defects. Their negative impact can be removed by post implantation high temperature annealing which results in optical activation of rare earth ions. Unfortunately high temperature annealing can lead to the decomposition of the GaN surface. In order to avoid this decomposition, a number of solutions have been proposed i.e. use of GaN proximity cap, annealing under high N2 overpressure (>10 exp 10 Pa), and recently implantation through a thin AlN cap layer epitaxially grown on top of GaN. By Rutherford backscattering and channeling (RBS/C), it was shown that the presence of the AlN layer allowed decreasing the implantation damage. It also provides an efficient way to protect the GaN surface for high temperature annealing. In this work, we investigate the structure, the behavior and the role during RE of the 10 nm AlN layer grown on GaN by MOCVD. We have carried out implantation at various fluences (1 to 40 exp 15atoms/cm2) at 300 KeV and we investigated the damage formation inside the layers. This structural analysis at the atomic scale of the layers and AlN/GaN the interface is done by high resolution transmission electron microscopy (HRTEM). It is shown that this layer avoids the formation of the highly damaged layer up to very high fluences. Our aim is to understand the protective role of AlN cap during implantation process, and this will be discussed in view of the microstructure of the implanted layers.

FF26.3
Atomic Ordering in $Al_xGa_{1-x}N$ Thin Films.
Adam T Wise and S. Mahajan; Chemical and Materials Engineering, Arizona State University, Tempe, Arizona.

AlxGa1-xN thin-film samples with aluminum contents of x_{Al}=0.27, 0.48, and 0.78 were grown on [0 0 0 1] oriented sapphire substrates using MOCVD. The III/V ratio and pressure were kept constant for

the growths, and an AlN buffer layer was used in all cases. [1 0 -1 0] and [1 1 -2 0] TEM samples were prepared from the as-grown specimens. These samples were examined using selected area electron diffraction (SAED) and weak beam dark field (WBDF) techniques to detect and characterize ordering. The SAED patterns for all samples showed diffraction spots at (0 0 0 1) positions in the [1 0 -1 0] zone axis, which was chosen to avoid double-diffraction. These spots can be shown to indicate 1:1 ordering using simple calculations. The SAED patterns also revealed streaking along the [0 0 0 1]direction for all samples. This streaking is caused by thin plates of 1:1 ordered regions on the (0 0 0 1) plane. The evidence for these particles and their shape results from an examination of multiple zone axes of the material, revealing a dependence of the [0 0 0 1] streak intensity on a zone axis used to obtain a pattern. The ordering in these samples is incomplete. The bulk of the samples remain un-ordered, as regions of 1:1 ordered material form in the matrix that is not ordered. arguments will be developed to rationalize the above results. The authors greatfully acknowledge the support of the above work by NSF.

FF26.4
Lattice defects of heavily doped Mg doped GaN.
Naoki Matsumura[1,2], Toshiyuki Obata[1,2], Kiyoshi Ogiwara[1], Hideki Hirayama[1], Yoshinobu Aoyagi[2,1] and Koji Ishibashi[1]; [1]Institute for Physical and Chemical Research(RIKEN), Wako, Japan; [2]Department of Electronics and Applied Physics, Tokyo Inst. Tech., Yokohama, Japan.

Mg is commonly used to realize p-type conductivity in GaN based materials. Heavy Mg doping is required to obtain high p-doping for sufficient deep-ultraviolet light emitting diodes. However, increase of the Mg doping invites the formation of extended defects such as vacancies, and interstitials. Furthermore, such defects play a role of dropping the carrier density. To solve these problems, lattice properties of Mg doped GaN should carefully investigated. In this study, we structurally characterized highly doped Mg:GaN by using the Rutherford backscattering spectrometry-channeling(RBS-c) method, which is highly sensitive to atomic displacements of the order of 0.1Á. Samples used in this study were grown by metalorganic chemical vapor deposition(MOCVD). Firstly, $Al_xGa_{1-x}N$(x<0.1) layer was grown on AlN/sapphire templates. Mg doped GaN was subsequently grown. Mg flow rate varies from 0(non-doped) to 180 sccm. RBS-c experiments were carried out by using RIKEN Pelletron type accelerator which has four-axis goniometer. 1.74-1.94 MeV H ions were used as probe beams to investigate <0001> channeling property. Scattering angle was 160°. Beam spot is 2mmϕ. In order to evaluate the crystalline quality, we used the normalized minimum yield(χ_{min}), which is defined as a ratio of yields in <0001> to those in random(off-axis). In general, the smaller the χ_{min} is, the better the crystalline quality is. Conductivity type of all samples used in this study are determined by Hall measurements. From the results of χ_{min} as a function of Mg flow rate(concentration), magnitude of χ_{min}(N) was significantly larger than that of χ_{min}(Ga). This result indicates that lattice defects of N atoms are more significant than those of Ga. Moreover, although χ_{min}(Ga) kept unchanged, χ_{min}(N) drastically increased from 30 to 90 sccm.These results indicate that Mg doping give more effects on N atoms than on Ga atoms. In order to identify the type of defects, incident ion energy dependence study was carried out. It is known that incident ion energy dependence of χ_{min} reflects the type of defects. The χ_{min} of point defects(dislocations) decreases(increases) as the incident ion energy increases. From the results of the χ_{min} as a function of incident ion energy, χ_{min}(N) monotonically increased with increasing incident ion energy, on the other hand, χ_{min}(Ga) decreased from 1.74 to 1.84 MeV, and increased from 1.84 to 1.94 MeV. These results suggest that the lattice defects of N atoms originated from dislocation and/or lattice deformation, and that the lattice defects of Ga were mainly point defects. It is well known that there are more than one type of defects in Mg:GaN, and they are basically inseparable by incident ion energy dependence. But, the tendency clearly reflects the dominant type of defects. As Mg was heavily doped, N atoms were strongly deformed, and N vacancies(V_N) were formed. Such vacancies made the neighboring Ga atoms point defects.

FF26.5
Characterization of lattice mosaic of *a*-plane GaN grown on *r*-plane sapphire by metalorganic vapor-phase epitaxy.
Kazuhide Kusakabe[1] and Kazuhiro Ohkawa[1,2]; [1]Applied Physics, Tokyo University of Science, Tokyo, Japan; [2]JST-ERATO, Tokyo, Japan.

We report on the characterization of lattice mosaic of *a*-plane GaN layers grown on *r*-plane sapphire substrates by atmospheric metalorganic vapor-phase epitaxy (MOVPE). In a general way, GaN-based semiconductors are grown over the polar *c*-plane. Recently, there has been an increasing interest to prepare nonpolar system such as *a*-plane and *m*-plane layers, due to an expectation to avoid polarization effects that cause a reduction of radiative efficiency. MOVPE and molecular beam epitaxy technique have been employed to obtain *a*-plane GaN but the crystal quality is inferior to that of *c*-plane films so far. X-ray rocking curve (XRC) is a convenient tool to estimate the lattice mosaic of epitaxial films. In this study, the anisotropic mosaic of *a*-plane GaN measured by XRC is discussed. Samples were grown by atmospheric MOVPE with a conventional two-step growth manner. XRC measurement was made by a Philips MRD system. The on-axis mosaic of *a*-plane GaN is orientation dependent for the scattering plane. XRC reveals that the full width at half maximum of (0001)-oriented scan (*c*-FWHM) is 1290 arcsec and that of (1-100)-oriented scan (*m*-FWHM) is 1440 arcsec for the layer grown at 1050 °C. For the sample grown at 1080 °C, *c*-FWHM shows equivalent value of 1250 arcsec while *m*-FWHM is reduced to 880 arcsec. This result suggests that anisotropy of growth mode is appeared. In the *a*-plane epitaxy, lateral growth for (1-100)-orientation is enhanced rather than (0001)-orientation with growth temperature increase. In fact, the stripe pattern along (1-100)-orientation on the surface is observed through optical micrograph when *a*-plane films are grown above 1100 °C.

FF26.6
Structural modifications in AlN/Si (111) substrates caused by N-ion implantation. Eric Irissou, Muhammad Jamil, James Grandusky, Vibhu Jindal and Fatemeh Shahedipour-Sandvik; College of Nanoscale Science and Technology, SUNY University at Albany, Albany, New York.

It was shown that significant reduction of dislocation density and elimination of cracks in overgrown GaN films are obtained by performing N-ion implantation of AlN/Si (111) substrates prior to the growth [1]. The ion implantation creates a defective layer in the Si (111) yielding a top Si layer that is believed to absorb most of the stress during the growth of GaN. In this paper we present results of the structural characterization of the AlN/Si (111) substrates at each stage of the process namely; before ion implantation after implantation, after annealing and after growth of GaN overlayer. For this study two physical parameters were varied. The thickness of the top Si layer and the thickness of the AlN layer. The ion implanted energy was varied from 50 to 200 keV resulting in a change in the projected range into the Si substrate. The thickness of the AlN buffer layer was varied from 10 to 80 nm together with adjustment of the implantation energy to keep constant the projected range in the silicon. Ion Implantation range and distribution was measured by means of Secondary Ions Mass Spectrometers using depth profiling technique. The results are compared with Monte-Carlo calculations performed on TRIM2003 software. Actual thickness, density, surface and interface roughness, lattice strain of the AlN and top Si layers before implantation, after implantation, after annealing and after growth of 2 μm thick GaN epilayer were measured by means of X-rays reflectometry and high-resolution x-rays diffraction. The results are presented in correlation with quality of the GaN overgrown layer. [1] M. Jamil, J. R. Grandusky, V. Jindal, and F. Shahedipour-Sandvik, Appl. Phys. Lett. Submitted (2005)

FF26.7
Pseudomorphic Stabilization of the Rocksalt Phase of GaN.
Vijay Rawat[1,2] and Timothy Sands[1,2]; [1]Materials Engineering, Purdue University, West Lafayette, Indiana; [2]Electrical and Computer Engineering, Purdue University, West Lafayette, Indiana.

There are three known polymorphs of GaN: wurtzite(w-GaN), zinc blende (zb-GaN), and rocksalt (rs-GaN). At ambient conditions, wurtzite (space group: $P6_3mc$) is the thermodynamically stable polymorph with a direct bandgap of Eg = 3.4 eV. It is this phase that forms the basis for most GaN device technology. The zb-GaN polymorph has been stabilized on the (001) crystal plane of cubic substrates such as Si, MgO and GaAs by overcoming the intrinsic tendency to form the wurtzite structure with the epitaxial compatibility. The rs-GaN polymorph (space group: Fm3m) is thermodynamically the most difficult to synthesize and is usually induced at very high pressures, of the order of 52 GPa, in diamond anvil cells but the crystal structure reverts back to the stable wurtzite form with the release of pressure. The electronic properties of rs-GaN phase are different than those of w-GaN and zb-GaN; theoretical investigations have predicted that rs-GaN is an indirect bandgap semiconductor with a bandgap of 1.7 eV. The wurtzite-to-rocksalt transition in AlN, another III-V compound which is similar to GaN in crystal structure, occurs at a lower hydrostatic pressure of 17 GPa. The rocksalt AlN phase (a=0.408 nm), an insulator, has been stabilized in epitaxial superlattices with the rocksalt metallic phases, TiN (a=0.424 nm) and VN (a=0.414 nm). If rocksalt GaN (a=0.408 nm-0.422 nm) could be similarly stabilized, it would be possible to fabricate true metal/semiconductor superlattices for applications in solid-state thermionic power generators. In the present work, we have grown 50-period TiN/GaN multilayers on (100) MgO substrates using reactive pulsed laser deposition in an ammonia ambient at elevated temperatures (550-750 °C). The TiN layer thickness was kept

constant at 10 nm while the GaN thickness was varied from 0.5 nm to 3 nm. X-ray diffraction studies revealed that when the GaN layer was thinner than 2 nm, it grew with the {100} oriented rocksalt structure on {100} oriented TiN layers. The strained lattice parameter of the rs-GaN phase was found out to be 0.422 nm. Currently, the critical thickness for the rocksalt-to-wurtzite transition in case of GaN, is being investigated as a function of the lattice constant of the metallic nitrides such as TiN, VN and ZrN(a=0.4585 nm). These results will be discussed in the context of a phenomenological model for psuedomorphic stabilization of rocksalt GaN and AlN.

FF26.8
Study of ELOG GaN for Application in the Fabrication of Micro-channels for Optoelectronic Devices.
Nathan John Berry Ann, Dimitris Korakakis, Kalyan Kasarla, Lee E. Rodak and Nanying Yang; CSEE, WVU, Morgantown, West Virginia.

Gallium Nitride (GaN) is a promising wide bandgap semiconductor material for many optoelectronic applications, especially in the near UV range. Over the past several years, an extensive technical effort has been focused on improving the quality of GaN films through various overgrowth techniques such as epitaxial lateral overgrowth (ELOG), facet controlled epitaxial lateral overgrowth (FACELO), and Pendeoepitaxy. ELOG has been shown to reduce the density of threading dislocations by up to five orders of magnitude1, however a complete physical model describing lateral overgrowth is needed in order to take full advantage of the process. A lateral overgrowth model will allow for the design and fabrication of three dimensional structures that can lead to novel devices and also to efficient biosensors by integrating micro and nano channels on the same chip as the optoelectronic components. A two-step process has been used to successfully control the geometry of overgrown GaN. Conditions have been identified which give a reduced lateral growth rate, in order to allow expansion of the (11-2n) plane to form vertical sidewalls and for the design of channel width. These geometries are being examined for possible application in laser diode and micro-channel fabrication for integrating bio-agent detection modules. References [1] Gibart, Pierre 2004 Rep. Prog. Phys. 67 667-715

FF26.9
Characterization and Properties of Extended Defects in GaN Stripes Via 3D Polychromatic Microdiffraction.
Rozaliya I. Barabash[1], G. E. Ice[1], C. Roder[2], S. Figge[2], S. Einfeldt[2], D. Hommel[2], T. M. Kantona[3], J. S. Speck[4], S. P. DenBaars[4] and R. F. Davis[5]; [1]Metals and Ceramics Div., Oak Ridge National Laboratory, Oak Ridge, Tennessee; [2]Institute of Solid State Physics, University of Bremen, Bremen, Germany; [3]Electrical and Computer Engineering Department, College of Engineering, University of California at Santa Barbara, Santa Barbara, California; [4]Materials Department, College of Engineering, University of California at Santa Barbara, Santa Barbara, California; [5]Materials Science and Engineering Department, North Carolina State University, Raleigh, North Carolina.

As dislocations are known to impair the performance of GaN-based light emitting devices, lateral epitaxial overgrowth (LEO) techniques have recently been developed which greatly reduce the density of threading dislocations. Pendeo- (PE) and cantilever epitaxy (CE) are the most promising among LEO growth techniques. The crystallographic tilt of the laterally growing wings relative to the seed (column) region usually accompanies all CE and PE GaN layers. Several questions are not yet answered: what is the trend of the wing tilt in CE GaN layers on Si(111) substrate and what are additional factors besides the difference in thermal expansion coefficients of the GaN layer and the substrate influencing the wing/seed tilt. The application of Polychromatic X-ray microdiffraction (PXM) to this complicated problem together with scanning electron microscopy (SEM), FE and high resolution X-ray diffraction (HRXRD) has enabled us to provide detailed new information about local strain and strain gradient, dislocations, misorientations and wing tilt in GaN layers. We show that in the CE or PE grown GaN layers the wings are tilted upward at room temperature. Depending on the growth conditions tilt boundaries may (or may not) be formed at the column/wing interface. It is possible to avoid the formation of the tilt boundary at certain growth conditions. A depth dependent deviatoric strain gradient is found in the GaN layers. The out of plane tilt angle between GaN (0001) and Si (111) is observed and quantified.

FF26.10
What does an (a+c) dislocation core looks like in wurtzite GaN ? Gerard Nouet[1], Imad Belabbas[1,2], Mohamed Akli Belkhir[2], Antoine Bere[1,4], Jun Chen[3], Sebastien Petit[1] and Pierre Ruterana[1]; [1]SIFCOM, ENSICAEN, Caen, France; [2]Laboratoire de Physique Theorique, University A.MIRA, Bejaia, Algeria; [3]LRPMN, IUT, Alencon, France; [4]LPCE, University, Ouagadougou, Burkina Faso.

Despite the improvements made in heteroepitaxial growth techniques, GaN layers still contain an important amount of dislocations, typically ranging from (10exp6) cm-2 to (10exp10). The majority of these dislocations are a-type, whereas c- and (a+c)-type dislocations are present with less important amounts. Although their number is reduced, c- and (a+c)-type dislocations were found to have profound effects on the electronic properties of GaN layers. Over the last decade, a-type and c-type dislocations were extensively investigated as well theoretically as experimentally. Then, for these dislocation cores, Z-contrast images are available [1] and atomistic models were provided [2]. Recently, using sophisticated aberration corrections, Arslan et al. [3] were able to provide the first Z-contrast image of an (a+c)-type dislocation core. They found it filled and exhibiting an 8-atoms ring structure. However, up today no atomistic model for this dislocation core is available. To fill this gap, we carried out an atomistic simulation of the (a+c)-type dislocation based on a modified Stillinger-Weber potential. This allowed us to treat large models, with about 28800 atoms, which is necessary due to the large Burgers vector of the dislocation. Two core configurations were found to be stable: an 8-atoms ring like-structure and a 5/7-atoms ring structure. These cores displayed neither dangling nor wrong bonds. [1]- Y. Xin, S. J. Pennycoock, N. D. Browning, P. D. Nelist, S. Sivananthan, F. Omnes, B. Beaumont, J. P. Faurie and P. Gibart, Appl. Phys. Lett., 72, 2680 (1998). [2]- A.T. Blumenau., C.J. Fall, J. Elsner, R. Jones, M.I. Heggie and Th. Frauenheim, Phys.Stat.Sol.(c), 0, 1684 (2003). [3]- I. Arslan, A. Bleloch, E.A. Stach and N.D. Browning, Phys.Rev. Lett., 94, 025504 (2005).

FF26.11
Electron backscatter diffraction and forescatter imaging of tilt, atomic steps and dislocations in nitride thin films.
Carol Trager-Cowan[1], Francis Sweeney[1], Pat Trimby[2], Austin Day[2], Ali Gholinia[2], Niels-Henrik Schmidt[2], Peter J Parbrook[3], Angus J Wilkinson[4] and Ian M Watson[5]; [1]Physics, Strathclyde University, Glasgow, United Kingdom; [2]HKL Technology, Hobro, Denmark; [3]EPSRC National Centre for III-V Technologies, Sheffield University, Sheffield, United Kingdom; [4]Materials, Oxford University, Oxford, United Kingdom; [5]Institute of Photonics, Strathclyde University, Glasgow, United Kingdom.

In this presentation we will describe the use of electron backscatter diffraction (EBSD) mapping and forescatter imaging to study tilt, atomic steps and dislocations in GaN thin films. Forescatter images are produced from backscattered electrons emanating at a shallow angle from the surface of a sample tilted at about 70° to the impinging electron beam. This forescatter detection geometry produces channelling contrast, where changes in the grey scale of the resulting image are related to crystallographic orientation. EBSD mapping of a series of GaN thin films of increasing thickness (ranging from 70 nm to 1600 nm) revealed that increasing the thickness of the layers resulted in a decrease in crystallographic tilt from $> 0.5°$ to $< 0.2°$. From our results we deduce that EBSD may be used to measure orientation changes in GaN thin films of the order of 0.1°. Forescatter images of the GaN thin films revealed the presence of threading screw dislocations located at the end of atomic steps. Dislocations may be imaged due to lattice plane tilting in the vicinity of the dislocations. The imaging of atomic steps in the SEM was unexpected and is tentatively attributed to channelling contrast resulting from lattice distortion at the steps. EBSD patterns were recorded along a line scan on the top surface of a just coalesced epitaxial laterally overgrown GaN (ELOG) thin film. EBSD pattern shifts were measured at [2-1-13], and [01-12] zone axes from which tilt distributions were deduced. A periodic change in tilt of $\pm$ 0.2° was measured. The tilt in the ELOG thin film was imaged using forescatter imaging. High resolution forescatter images revealed changes in the distribution of dislocations in the film.

SESSION FF27: Poster Session: VPE
Chairs: Leah Bergman and Nicolas Grandjean
Thursday Evening, December 1, 2005
8:00 PM
Exhibition Hall D (Hynes)

FF27.1
Growth of GaN layers on Si(001) by MOVPE. Fabian Schulze, Juergen Blaesing, Armin Dadgar, Thomas Hempel, Till Riemann, Anette Diez, Juergen Christen and Alois Krost; Insitute of Experimental Physics, Otto-v.-Guericke University Magdeburg, Magdeburg, Germany.

The Si(001) substrate orientation offers an evident approach for the integration of GaN-based devices with the standard silicon technology, because this orientation is mainly used in silicon mainstream technology. However, the main challenges are the different lattice symmetries and crystallographic orientations of GaN and Si(001). We present structural and optical inves-tigations on GaN layers on

Si(001) grown by metalorganic vapour phase epitaxy (MOVPE). The use of high temperature AlN-seed layer leads to solely c-axis orientated GaN on Si(001). In this case two in-plane alignments appear due to the symmetry of the silicon surface. There-fore, to get a smooth and fully closed GaN layer on Si(001) the selection of only one in-plane orientation is necessary. Using 4° off-oriented Si(001) substrates allows to grow GaN on Si(001) with one well defined in-plane alignment. We achieve a flat and fully coalesced c-axis oriented GaN layers on Si(001). The crystallographic structure of the samples is investigated by X-ray diffraction measurements, in particular by $\theta/2\theta$-scans, pole-figures and grazing inci-dence diffraction. The achieved FWHM of the GaN(0002) rocking curve is 420// and the in-plane distribution is 1,8°, determined on GaN(10-10) ω-scan. The surface morphology was analyzed by means of FE-REM imaging and AFM, and the optical properties by photo- and cathodoluminescence. Furthermore, we will present GaN based test devices on Si(001) such as LEDs and HEMT- structures.

FF27.2
A Comparison between HVTE and MOCVD Growth of AlN - Influence of the Growth Conditions. Vladimir Tassev[1], David Bliss[2], David Weyburne[2], Sheng Qi Wang[1], Ronnie Synakowski[2], Jeffrey Anthis[3] and Nam Nguyen[3]; [1]Solid State Scientific Corporation, Hollis, New Hampshire; [2]Air Force Research Laboratory, Hanscom AFB, Massachusetts; [3]Epichem, Inc., Haverhill, Massachusetts.

The HVTE and MOCVD approach for growth of aluminum nitride are compared in a parallel study based on a wide variety of growth conditions. The experiments were conducted in a three-inch diameter fused silica horizontal reactor, using $AlCl_3-^t$ butyl and TMA as precursors and silicon carbide; bare sapphire and thin AlN templates as substrates. Growth temperatures, reactor pressures and total flows in the ranges of 1100^0C $-$ 1300^0C, 2.6 $-$ 40 Torr, and 1000 $-$ 1500 sccm, respectively, were applied in order to determine the influence of the different growth conditions on the final layer quality. The initial stage of growth was studied as well. The in-situ optical interference curve of a laser reflected from the growing layer surface was used to determine the momentary growth rate and the quality of the film surface during the process. The post-growth characterizations including SEM, XRD and AFM provided the information feedback to optimize the applied growth conditions. It was observed that the deposition temperature is the parameter with the strongest influence on the growth process in comparison to the reactor pressure or to variation of gas flows. It was established that from the point of view of surface morphology (AFM) the best substrate temperature is about 1300^0C, while the best structural quality (XRD) was achieved at about 1100^0C. The optimal pressure was about 5 Torr, with both precursor and ammonia flows maintained at a low rate, while the carrier gas flow was held at a high rate. It was found that a thin AlN template deposited in advance on sapphire is the most suitable substrate for thick layer growth, but direct deposition on bare sapphire gave also good results and might be additionally optimized. A study of the initial stages of growth showed that at high temperature nucleation starts in a number of points on the sapphire surface. Then coalescence of the islands begins after 45 sec of growth and finishes completely in the next 75 sec. The best results in the discussed series of experiments showed surface roughness less than 1 nm and FWHM in the ranges of 200 and 1500 arc-sec for reflection 002 and 102, respectively. The surface topology proved the layers possess good thickness uniformity. The growth rate for AlN layers is in the range of 2 to 7 μm/h.

FF27.3
AlN epitaxy on (0001) sapphire. Seungjong Lee, Dae-woo Kim and Subhash Mahajan; Chemical and Materials Engineering, Arizona State Univ., Tempe, Arizona.

AlN is one of the most promising group III- nitrides because of its direct wide band gap (6.2eV), high temperature stability and high thermal conductivity. These properties make AlN suitable for many applications in optoelectronics, high power and high temperature devices. In the absence of a suitable substrate, sapphire has remained the most commonly used substrate for III- nitrides epitaxy due to its low cost. Due to the large lattice mismatch and difference in thermal expansion coefficients between AlN and sapphire, AlN film grown by conventional two-step process MOCVD on sapphire exhibits poor structural quality and surface morphology. In the present study, high quality AlN layers were deposited on (0001) sapphire substrates by the two-step epitaxy using metal organic chemical vapor deposition. The deposition of low temperature AlN nucleation layer (NL)s preceded the high temperature AlN overgrowth. The approximate growth temperature for the NL and over layer were 460 $\sim$ 890°C and 1190°C, respectively. The nucleation time ranged from 15second to 7minutes. Before the initiation of high temperature AlN over-layer growth, the NL underwent high temperature annealing. The influence of AlN NL growth temperature and time was examined by atomic force microscopy (AFM), X-ray diffraction (XRD), transmission electron microscopy (TEM) and photoluminescence (PL). Three interesting observations have emerged from the preceding study. First, the narrowest X-ray rocking curve and flat surface are obtained when AlN NLs are grown at 510°C and 30second. Using these conditions, the (0002) FWHM value is 251 arc seconds, a value which is close to those obtained in device-quality GaN layers. AFM shows that the crystal quality improves as the surface roughness of the NL and over-layer is decreased. The structural and optical properties of AlN layers are strongly dependent on the surface morphology and thickness of the NL, which in turn depends on its deposition time and temperature. Second, AlN layer grown on the optimal NL has very low density of inversion domain (ID)s, whereas other films have high density of IDs. Cross-sectional TEM images reveal that AlN deposited on the smooth NL surface has a smooth over-layer surface. Conversely, AlN deposited on the rough NL surface has a rough over-layer surface and high ID boundary density. Rough NLs have higher density of islands. Islands have (0001) flat top surfaces and pyramidal side facets which composed of (1_102) and (_1102) planes. Since WZ structure is non-centro symmetric, IDs originate from the each side facets and AlN has mixed polarity. Third, AlN layers with high IDs shows better optical property. PL results show that the exciton peak is stronger in the case of high ID density AlN films. The inversion domains in the mixed polar films may confine carriers and thus enhance their recombination, resulting in increased luminescence.

FF27.4
Two-step Annealing of GaN Buffer Layers for High-quality $Al_xGa_{1-x}N$ (x $\approx$ 0.35) by Low-pressure MOCVD. Misaichi Takeuchi[1,2], Shigenori Hayakawa[2], Ryo Kajitani[2], Toru Kinoshita[3,2], Koji Kawasaki[2], Kazuya Takada[3] and Yoshinobu Aoyagi[2,3]; [1]RIKEN, Wako, Japan; [2]Tokyo Institute of Technology, Yokohama, Japan; [3]TOKUYAMA, Tokyo, Japan.

Deep UV (DUV) light emitting devices have been desired as one of the next generation of optoelectronic devices. AlGaN-based III-nitride semiconductors have attracted many researchers due to their wide-range tunable band gaps corresponding to 200 - 360 nm wavelengths. However, it is quite difficult to achieve high-quality AlGaN layers, because stable and controllable buffer technologies for them are not available at present. Some research groups utilize MOCVD-grown thin AlN layers as a template with considering its transparency for DUV and high-temperature stability. The quality of AlN layers is quite sensitive to treatment of sapphire substrates prior to the growth (polarity problem) and the growth process. On the other hand, sophisticated procedure of growth thin low-temperature GaN (LT-GaN) buffer layers on sapphire and their annealing causes the success of blue LEDs. Three-dimensional (3D) nucleation and faceting by that effectively relax the lattice mismatch between sapphire and epi-layers and drastically reduce the dislocation density in the blue LEDs. Recently, our group has succeeded in vertical-type DUV LEDs with development of laser lift-off technique and DUV-transparent electrodes for n-doped layers. For laser lift-off technique, melting layers should be inserted between sapphire substrates and DUV device structures (bottom n-doped layers). Therefore, use of LT-GaN buffer layers for AlGaN-based DUV LEDs is reasonable choice. Additional new growth procedures with conventional LT-GaN process are reported concerning with the quality of AlGaN layers in this paper. Samples were grown by a low-pressure MOCVD. TMG, TMA and NH_3 were introduced as the source gas, and H_2 as the carrier gas. 20 nm-thick LT-GaN buffer layers were grown on c-plane sapphire substrates after H_2 thermal cleaning. Amorphous-phase LT-GaN layers were transformed into 3D GaN crystalline nuclei by ramping the wafer temperature up to 1050 °C under NH_3 flow (1st anneal). This is the conventional LT-GaN growth and its annealing process. The sample showing the sharpest X-ray diffraction peaks was grown by the following procedure: conventional growth and anneal of LT-GaN, growth of a 130 nm-thick GaN layer which was grown to form clear GaN facet structure, 2nd anneal by stopping TMG flow and ramping up the wafer temperature in NH_3 atmosphere, ten-period $Al_{0.35}Ga_{0.65}N$ (20 nm)/AlN (5 nm) superlattices (SLs) to avoid wafer cracking, 1 μm-thick i-$Al_{0.35}Ga_{0.65}N$, and AlGaN-based DUV LED structures (n-AlGaN, AlGaN quantum well active layers, p-AlGaN and p-GaN). During the 2nd anneal, the surface flatness was recovered from the facet structure by the 130 nm-thick GaN growth (anneal flattening). We deduced that some kind of mass transport from facet structure was promoted in nano scale by anneal flattening during the 2nd anneal and affected the propagation of the threading dislocations. The detailed mechanism will be reported at the conference site.

FF27.5
Domain Matching Epitaxy of Cubic and Hexagonal Gallium Nitride Films on Saphhire Substrates. Jagdish Narayan[1], Punam Pant[1], Amit Chugh[1], Hong Choi[2] and John C. C. Fan[2]; [1]Department of Materials Science and Engineering, North Carolina State University, Raleigh, North Carolina; [2]Kopin Corporation, Taunton,

Massachusetts.

To obtain device-quality uniform gallium nitride films on substrates with a large lattice misfit such as sapphire, we propose the growth of single-crystal initial layer at low temperatures (500-700^{0}C), followed by second and third layers at higher temperatures (700-1050^{0}C). The crystal structure of initial layer is cubic (Zinc Blende) and is determined by growth parameters, specifically temperature and nitrogen cracking efficiency. The lower substrate temperatures and nitrogen deficiency favor the formation of cubic phase and stacking faults. The initial layer (also referred to as nucleation layer or low-temperature layer) with Zinc Blende structure grows epitaxially with the substrate via domain matching epitaxy, where integral multiples of planes match across the film-substrate interface. At lower temperatures of growth (~530^{0}C), the initial layer has cubic (Zinc Blende) structure, which grows with the following epitaxial relationships: $<111>_{ZBGaN}// <0001>_{sap}$ and $<110>_{ZBGaN}//$ $<10\text{-}10>_{sap}$. The cubic ZB GaN transforms to hexagonal (Wurtzite) structure during subsequent heating or forms directly at the higher temperature growth. The film having Wurtzitic structure has the following epitaxial relationships: $<0001>_{hGaN} // <0001>_{sap}$ and $<\text{-}2110>_{hGaN}// <10\text{-}10>_{sap}$. The transformation from cubic to hexagonal structure occurs via annealing or removal of stacking faults. The hexagonal structure is preferred as a template for higher-temperature growth, however, cubic structure, which is a defective hexagonal with stacking faults in alternate layers, can provide a template for epitaxy. The role of Shockley partials terminating at the island edges in the generation of threading dislocations is discussed.

FF27.6
The Polarity Control of LP-MOVPE GaN by N_2 Carrier Process.
Seiji Mita, Ramon Collazo, Raoul Schlesser and Zlatko Sitar; Dept. of Materials Science and Engineering, North Carolina State University, Raleigh, North Carolina.

The polarity control of GaN films grown on c-plane sapphire substrates by LP-MOVPE using N_2 as carrier and diluent gas was investigated in detail. The control of the polarity type depended on the substrate preparation prior to the actual HT-GaN growth. GaN films grown directly on sapphire were found to be Ga-polar (+c), while GaN films grown on nitrided substrates were N-polar (-c). N-polar GaN grown using N_2 carrier and diluent gas exhibited 2.5 nm RMS roughness without hexagonal features. Device quality Ga-polar GaN was obtained by using a LT-AlN buffer layer followed by a specific annealing process. Optimized buffer layer thickness was 10 nm, with an annealing time of 20 min and a temperature of 1050 °C. By using these conditions for the buffer layer growth, mirror-like Ga-polar GaN was grown using a V/III ratio of 100. The x-ray rocking curve full width at half maximum (FWHM) of Ga-polar GaN films was around 350 arcsec for the symmetric (00.2) reflection and around 550 arcsec for the skew-symmetric (10.3) reflection. The surface roughness was measured by AFM to be 0.2 nm RMS and the growth rate was estimated at 2.0 μm/hr. These results suggest that by using N_2 carrier, one can achieve films of the same quality as those grown by using H_2 dilution. From a thermodynamic point of view, the driving force for the deposition decreases with the increase in the mole fraction of hydrogen relative to nitrogen in the carrier gas. For the case of N_2 as carrier gas, it can be predicted that GaN can be grown with a V/III ratio an order of magnitude lower than by using solely H_2 as carrier gas. In addition, such a low V/III ratio offers significant advantages in the manufacturing process, e.g. it enables a significant reduction in process cost and an increase in process safety. Experimental details and characterization results of polarity-controlled GaN films will be presented.

FF27.7
Effects of GaN template annealing on the optical and morphological quality of the homoepitaxial overgrown GaN layer.
James Grandusky, Vibhu Jindal, Muhammad Jamil, Eric Irissou and Fatemeh Shahedipour-Sandvik; Optoelectronics, College of Nanoscale Science and Engineering, University at Albany, Albany, New York.

Growth of GaN based devices such as light emitting diodes and laser diodes often occurs on already prepared GaN templates grown on native (e.g. bulk GaN) and non-native (e.g. sapphire) substrates. High temperature annealing methods that are generally used for growth on other substrates can not be completed on GaN templates due to the decomposition at temperatures above 800 ^{o}C in hydrogen rich ambient. The decomposition rate is higher than the Ga desorption rate from the surface under most conditions and causes Ga droplets to form on the surface, which can hinder further growth. In situ annealing conditions were developed for annealing the GaN templates to remove any contamination while preventing significant Ga droplets from accumulating on the surface in both H2 and N2 environments to obtain optimized annealing conditions. The effect of the annealing conditions on the GaN homoepitaxy on GaN templates is presented. The structural properties were studied by XRD measurements while Photoluminescence measurements and Hall measurements studied the optical and electrical properties respectively. The results of the experiments will be presented along with the significance of these experiments for growth on bulk GaN substrates. Bulk substrates are subjected to polishing damage that is known to effect the surface and initial growth nucleation. These results will be especially important when considering vertical conduction occurring through such a GaN substrate. This work was supported by General Electric Global Research located in Niskayuna, NY.

FF27.8
Predicting ELO GaN Growth Morphologies: Tools for Design.
Danxu Du[1], David J. Srolovitz[1], Michael E. Coltrin[2] and Christine C. Mitchell[2]; [1]Dept. of MAE, Princeton University, Princeton, New Jersey; [2]PO Box 5800, Sandia National Laboratories, Albuquerque, New Mexico.

In epitaxial lateral overgrowth, GaN is grown through windows in a mask layer. Typically, GaN growth through these windows and onto the mask surface is highly faceted. The growth morphology (shapes, facets) can be manipulated through modification of growth reactor conditions and by modification of the shapes of the windows etched into the mask layer. In the present study, we grow GaN through a variety of window shapes. From the observations of the pre-coalescence islands, we derive the fundamental function (the velocity vs. surface normal v(n)) that describes growth. The GaN was grown on a dry etched silicon nitride mask layer using trimethylgallium and ammonia MOCVD at 1050C and the resultant morphologies analyzed using SEM. Symmetry and Herring's theorems were employed to solve the inverse problem to obtain the velocity function v(n) for these growth conditions. Using this v(n), we perform level-set method simulations of the growth of GaN islands for the large variety of window shapes employed in the experiments. The simulations are able to reproduce essentially all features of the island morphologies. These morphologies include faceted and curved surfaces. Based upon the success of this method, we propose a simple series of experiments to determine v(n) for all interesting experimental conditions using a single mask. Further, given this result, we can quantitatively predict growth morphologies as a functions of window shape and growth conditions. Most importantly, this approach can be used for the quantitative design of desired growth features - shape, facets, etc.

FF27.9
Investigation of GaN Layer Morphology Development During The Epitaxial Growth of GaN Layers by MOCVD using the Ga Treatment Step Method.
Andrzej Pawel Grzegorczyk[1], Corina E. C. Dam[1], Paul R. Hageman[1], Jan L. Weyher[1,2] and Poul K. Larsen[1]; [1]Exp. Solid State Physics III, Institute for Molecules and Materials, Radboud University, Nijmegen, Netherlands; [2]Institute of High Pressure Physics, Polish Academy of Sciences, Warsaw, Poland.

The microscopic evolution of GaN layers, grown by metal-organic chemical vapor deposition (MOCVD) on α-Al2O3 using a new Ga treatment step method (GTS), was investigated. Annealing the c-plane sapphire in trimethylgallium (TMG) at the same temperature as used for the growth of the main GaN layer allows the subsequent deposition of high quality material with a dislocation density comparable with the standard two-step growth method. This new method simplifies the growth process because the deposition of a low temperature (and high pressure) GaN nucleation layer can be omitted. Based on the total weight of sapphire substrate before and after the annealing treatment, the thickness of a deposited Ga metal layer is estimated to be in the range of a single atomic layer. With the help of in-situ reflectance measurements the coalescence and overgrowth of the GaN epilayers deposited on these Ga metal layers were observed. To visualize the development of the surface morphology during the growth, series of samples were prepared with different thickness of main GaN layers. Ex situ characterization was made by scanning electron microscopy and atomic force microscopy. The experimental results demonstrate that it is possible to control the GaN epitaxial layer polarity by adjusting the annealing time. By using orthodox etching in molten KOH-NaOH eutectics the dislocation density and N-polar inclusion density were revealed. Photoluminescence measurements were performed at 4K in order to determine the optical properties of the GaN layers. The PL data shows that D_0X peak position is shifted toward the high-energy side compared to standard two-step growth method, which suggests that the samples are under high compressive strain at room temperature.

FF27.10
Layer Transfer of GaN Layer Growth on Porous GaN Sublayers onto a Desirable Substrate.
Tien-Hsi Lee[1,2], Bao-Jen Pong[3], Van-Ga Liao[1] and Tsu-Wu Chiang[1]; [1]Mechanical Engineering, National Central University, Chung-Li City, Taiwan; [2]Institute of Materials Science and Engineering, National Central University,

Chung-Li City, Taiwan; [3]Optical Sciences Center, National Central University, Chung-Li City, Taiwan.

Epitaxial GaN sublayer was grown by MOCVD on SiC seed wafer and then the surface of GaN sublayer on the SiC seed wafer was subjected to an electrochemical process to create a porous sponge structure. A GaN layer was epitaxially grown over the surface of porous GaN sublayer on SiC wafer. The porous GaN structure can enable not only strain relaxation condition in crystal growth on a dissimilar substrate to allow growth of residual stress-free and high quality crystalline epitaxial layers of GaN but also weak mechanical strength for layer splitting in layer transfer step. The surface of the GaN layer was then activated by a plasma treatment to form a bondable surface, which was then bonded with a handle wafer. After a low temperature treatment, the seed wafer was split by water jet at the porous layer. Finally, a CMP process was preformed to remove the porous layer remaining over the handle wafer and to smoothen the surface of transferred GaN layer on handle wafer. The bonding result can be design to strong enough for following layer splitting but not resist high temperature during future thick GaN layer growth process by bubble generation in bonding interface, that is, the thick GaN layer could be lifted off from the handle wafer after high temperature growth process. The transferred GaN layer bonded on the handle wafer is proposed as a seed template for the crystal growth of thick GaN without thermal stresses.

FF27.11
MOVPE Growth of AlGaN/AlN on Native AlN Substrates for Device Applications. Wayne Liu[1], Sandra Schujman[1], James Grandusky[2], Fatemeh Shahedipour-Sandvik[2], Kai Liu[3], Michael Shur[3], Thomas Gessmann[3], Yangang Xi[3], E. Fred Schubert[3] and Leo Schowalter[1]; [1]Crystal IS, Inc., Green Island, New York; [2]State University of New York at Albany-SUNY, Albany, New York; [3]Rensselaer Polytechnic Institute, Troy, New York.

In this paper, we report on metal-organic vapor-phase epitaxy (MOVPE) growth of AlGaN/AlN on AlN substrates and the discovery of new surface morphology patterns on the substrates and the epilayers. AlN substrates with different orientations have been selected for epitaxial growth of AlGaN/AlN materials. The epilayers were characterized using photoluminescence (PL), high resolution X-ray diffraction (HRXRD), and atomic force microscopy (AFM). For the first time, we have observed several interesting growth patterns related to substrate morphology, epigrowth nucleation, and epilayer surface morphology. Closed-loop hexagonal rings, spirals, parallel atomic level steps, and mixtures of those structures have been observed and studied on AlN substrates and AlGaN/AlN epilayers. The characterization data show that substrate orientation, surface morphology, and growth conditions play an important role in forming different kinds of surface morphologies. The HRXRD and PL measurement data, FWHM and luminescence intensity, show that the epilayer quality is better than that of grown on non-native substrates. Finally, the results of application of MOVPE growth of AlGaN/AlN for device structures such as UV LEDs and HFET will be discussed.

FF27.12
Crack Reduction in AlGaN/GaN using an AlN Interlayer.
Peter D Cherns, Clifford McAleese, Jon Barnard, Menno J Kappers and Colin J Humphreys; Department of Materials Science and Metallurgy, University of Cambridge, Cambridge, United Kingdom.

There is great interest in optoelectronic devices based on AlGaN/GaN structures emitting at UV wavelengths. However, AlGaN layers deposited epitaxially on GaN are under tensile strain and tend to crack above a critical layer thickness, which decreases with increasing Al content. This can be alleviated by growing a thin layer, typically 30nm, of AlN between the GaN and AlGaN. The AlN interlayer places the AlGaN under compressive strain, enabling thicker layers of crack free AlGaN to be grown. The present study examines the implications of using an AlN interlayer to grow AlGaN on GaN templates and the mechanisms by which relaxation of the interlayer occurs. AlGaN/AlN/GaN layers were grown by metal organic vapour phase epitaxy (MOVPE). Samples were prepared both in plan-view and in cross-section, and studied by transmission electron microscopy (TEM) and scanning transmission electron microscopy (STEM). The distribution of Al in the interlayer was examined using high angle annular dark field (HAADF) imaging, electron energy loss spectroscopy (EELS) and energy filtered TEM (EFTEM). Results indicate that no part of the interlayer contains pure AlN, but instead a range of compositions of AlxGa1-xN. It is observed that the Al in the layer is accumulated at the top of the layer. The mechanism for strain relaxation was examined as a function of the interlayer thickness. Samples with AlN interlayer thicknesses of 1, 5, 10, 30 and 50nm were studied. It is found that the critical thickness of AlN at which an interlayer of this type will prevent formation of cracks in AlGaN is ∼5nm. Above 5nm thickness, interlayer cracks in AlN were observed, and studied with a combination of lattice imaging, HAADF, EELS and EFTEM. Within the cracks, Ga-rich AlGaN was observed, along with voids extending into the GaN. Regions of the AlGaN layer directly above the cracks were found to have reduced Al content. In addition, the cracks were found to be associated with additional edge-type threading dislocations. Weak-beam dark field (WBDF) imaging showed evidence for the nucleation of dislocation loops, and the subsequent bending up of misfit dislocations generated at the GaN/AlN interface. Bright field (BF) TEM imaging has been used to examine the correlation between misfit dislocation generation and the cracking of the interlayer. A model will be proposed for the relaxation of the strain in the interlayer in this system, by a combination of small scale cracking and dislocation generation.

SESSION FF28: Poster Session: MBE
Chairs: Leah Bergman and Nicolas Grandjean
Thursday Evening, December 1, 2005
8:00 PM
Exhibition Hall D (Hynes)

FF28.1
Intrinsic Surface Structures of c-GaN(001) Studied by Scanning Tunneling Microscopy. Arthur R. Smith[1], Hamad Al-Brithen[1], Rong Yang[1], Muhammad Haider[1], Costel Constantin[1], Erdong Lu[1], Nancy Sandler[1] and Pablo Ordejon[2]; [1]Physics & Astronomy, Ohio University, Athens, Ohio; [2]ICMAB - CSIC, Campus de la U.A.B., Barcelona, Spain.

Due to the importance of surface structure in epitaxial growth of materials, native surface reconstructions have been studied intensely for a wide variety of semiconductor and metal surfaces. Reconstructions on c-GaN(001) were reported by several groups using scanning tunneling microscopy (STM) and reflection high energy electron diffraction (RHEED), including 1x1, 2x2, c(2x2), and $sqrt10$ x $sqrt10$-R18.4°.[1,2] However, several of these structures were later reproduced by exposing the clean surface during growth to an arsenic background, whereas without the As, only 1x1 and 4x1 were observed in diffraction.[3] To examine in real space the intrinsic, clean surface structures of c-GaN(001), we have performed a new STM study using a combination molecular beam epitaxy (MBE)/STM system. Cubic GaN(001) surfaces are prepared by rf N-plasma MBE on MgO(001) substrates and transferred through UHV to the adjoining STM chamber. It is found that the clean surface has the following group of reconstructions: 4x3, 4x7, c(4x16), and c(4x20). The 4x3 occurs after removal of excess Ga from the growth surface and corresponds to the 4x1 seen in diffraction; this reconstruction is seen both at 300K and at the MBE growth temperature. While a unique Ga tetramer model structure was proposed for the 4x1,[4] the 3x period observed in our STM data, which is not seen in diffraction, shows that a new or modified model is needed to explain this structure. The 4x7 and other higher order reconstructions are Ga-adatom based, consisting of additional Ga on the (001) surface. These reconstructions undergo disordering above several hundred degrees C, resulting in a 1x1 RHEED pattern. [1] O. Brandt et al., Phys. Rev. B 52, R2253 (1995). [2] M. Wassermeier et al., Surf. Sci. 385, 178 (1997). [3] G. Feuillet et al., Appl. Phys. Lett. 70, 1025 (1997). [4] Joerg Neugebauer et al., Phys. Rev. Lett. 80, 3097 (1998).

FF28.2
Real-time synchrotron x-ray studies of high and low temperature nitridation of c-plane sapphire. Yiyi Wang[1], Ahmet S. Ozcan[1], Gozde Ozaydin[1], Karl F. Ludwig[1], Hua Zhou[2], Randy Headrick[2], Anirban Bhattacharyya[3], Theodore D Moustakas[3] and David Peter Siddons[4]; [1]Physics, Boston University, Boston, Massachusetts; [2]Physics, University of Vermont, Burlington, Vermont; [3]Electrical and Computer Engineering, Boston University, Boston, Massachusetts; [4]National Synchrotron Light Source, Brookhaven National Laboratory, upton, New York.

The early-stage nitridation kinetics of c-plane sapphire with a radio frequency (rf) nitrogen plasma source at both low (300?C) and high (750?C) temperature was examined using grazing-incidence real-time x-ray diffraction, in-situ x-ray reflection and in-situ reflection high-energy electron diffraction (RHEED). The grazing-incidence real-time surface-sensitive x-ray scattering study examined the temporal evolution of the AlN (10-10) peak intensities, which are proportional to the volume of AlN material. The peak intensities have been converted to equivalent film thickness using the reflectivity fit results. The change from sapphire to AlN structure at the surface is also verified by in-situ reflection high-energy electron diffraction (RHEED). The real-time diffraction measurement shows the strain relaxation of the nitridation layer at both high and low temperatures as a function of increasing AlN thickness. However, the AlN growth rates are significantly different for the two temperature ranges. In both cases, the real-time x-ray diffraction data suggest that the early stage nitridation is governed by a nucleation and growth process. The

high temperature nitridation occurs rapidly and it continues for the experimental time period at an approximately linear rate. However, the rate of nitridation at low temperature slows down after approximately 70 minutes and reaches saturation after 150 minutes.

FF28.3
Growth of Nonpolar AlN and AlGaN on 4H-SiC (1-100) by Molecular Beam Epitaxy. Rob Armitage[1], Jun Suda[1,2] and Tsunenobu Kimoto[1]; [1]Department of Electronics Science and Engineering, Kyoto University, Kyoto, Japan; [2]PRESTO, Japan Science and Technology Agency, Kawaguchi, Japan.

There is growing interest in epitaxy of nonpolar crystal orientations of GaN due to their potential advantages in light-emitting devices. However, there is still room for improvement in nonpolar GaN growth techniques since the epilayer quality remains inferior to that of state-of-the-art GaN (0001). In addition to GaN, nonpolar orientations of AlN should be investigated given the applications of Al-rich AlGaN layers in deep-UV emitters. Surprisingly, the (1-100) orientation of AlN has hardly been characterized at all up to now. In the present study (1-100) AlN and AlGaN are grown on 4H-SiC by MBE and the layers are characterized by RHEED, AFM, high-resolution XRD, Raman scattering, and CL. The results indicate that 4H-SiC (1-100) is a promising substrate for development of nonpolar AlGaN of high structural quality. RHEED intensity oscillations are clearly observed during the initial stages of AlN growth at 950°C for an optimal Al/N ratio. Moreover, the RHEED streak spacing along the <11-20> azimuth for AlN layers over 300 nm thick is very close to that of the SiC substrate before growth. The geometry of the <11-20> RHEED pattern indicates that a metastable 4H phase of AlN grows on 4H-SiC (1-100). Stabilization of AlN in the 4H structure is in fact desirable to minimize formation of stacking defects at the interface. Optimal growth occurs for an Al/N ratio just below the droplet limit, and a corresponding 1×2 surface reconstruction is observed after growth. The crystalline quality of (1-100) AlN epilayers assessed by high-resolution XRD is remarkably high. In a set of 10 epilayers, XRD FWHM values less than 100 arcsec were consistently obtained for omega-scans of both the symmetric (1-100) and asymmetric (10-12) reflections, with best values of 40 and 50 arcsec, respectively, for a 250 nm AlN layer. The layers exhibit anisotropy in their XRD characteristics: the (1-100) rocking curve is narrowest when measured with the x-ray beam parallel to <11-20>, while the FWHM increases by about 50% when oriented parallel to the <0001> direction. The high AlN structural quality can be attributed to the coherent interface with the substrate and relatively close match in lattice parameters. For (1-100) AlGaN alloys grown on AlN buffer layers, the omega-scans broaden with increasing Ga content, but quality similar to that of the underlying AlN nucleation layer can be preserved for compositions below 30% Ga. The surface morphology of (1-100) AlN layers observed by AFM also shows an anisotropic structure. Long stripe-like features are observed running along the <11-20> direction, a feature common to the morphology of (1-100) GaN. The AlN growth surface exhibits an rms roughness of 0.5 nm for a 5 micron scan area. A comparably smooth surface is obtained for AlGaN grown on an AlN buffer layer. Our ongoing work involves growth of AlN/AlGaN superlattices and optical characterization.

FF28.4
Epitaxial c-GaAs/h-GaN heterostructures.
Vladimir Chaldyshev[1], Nikolay Bert[1], Yurii Musikhin[1], Bent Nielsen[2], Emilio Mendez[2], Zhixun Ma[3] and Todd Holden[3]; [1]Ioffe Institute, St. Petersburg, Russian Federation; [2]State University of New York at Stony Brook, Stony Brook, New York; [3]Brooklyn College of the City University of New York, Brooklyn, New York.

The recent spectacular progress in the growth technology of hexagonal GaN and related materials has resulted in bright blue and green LED's that are now commercially available in addition to traditional red AlGaAs/GaAs LED's. This makes a basis for the full spectrum of efficient RGB lightning. So the integration of these three RGB sources in a single chip becomes an emerging task. While blue and green LED's can be relatively easily combined in a single III-nitride epitaxial structure, the integration of wurtzite GaN and zinc-blende GaAs is a challenging material problem due to differences between hexagonal and cubic symmetries and huge (~20%) lattice mismatch. In this paper we first show that in spite of this problem an epitaxial c-GaAs/h-GaN heterostructure can be successfully grown. The 1-μm thick zinc-blende GaAs (111) films were grown on wurtzite GaN (0001) layers with sapphire substrates. We utilized a Varian dual-chamber MBE system and realized the epitaxial growth at 600 C with the rate of 1 μm/h. The GaAs films showed good adhesion to GaN and their surface had a large mirror-like area. The surface profile was characterized by atomic-force microscopy, which gives an average roughness of 10 nm for a 5x5 μm scan. Micro-Raman characterization and transmission electron microscopy (TEM) confirmed reasonably good crystalline quality of the GaAs films. The TEM study revealed a flat and abrupt epitaxial GaAs/GaN interface, but as a result of mismatch relaxation the films showed nanocavities at the interface and a large number of dislocations penetrating into the bulk of the GaAs films. Spectroscopic ellipsometry showed sharp interference fringes and characteristic behavior of the Ψ and Δ parameters in the range of 0.75-5.3 eV. Simulation of the optical properties of the GaAs/GaN/sapphire heterostructure indicates a reasonably good optical quality of the layers and interfaces. Photoluminescence measurements from 17 to 300 K revealed radiative recombination through band tails, as well as dominance of non-radiative processes. In conclusion, our results show reasonably good quality of the c-GaAs/h-GaN heterostructures and prove general feasibility of the epitaxial integration of III-nitrides and traditional III-V's.

FF28.5
Engineered Substrates for GaN Applications: Recent Progess for SopSiC Substrates. Bruce Faure[1], Alice Boussagol[1], Hacene Larheche[2], Severine Bressot[1], Philippe Bove[2] and Fabrice Letertre[1]; [1]Soitec, Bernin, France; [2]Picogiga International, Courtaboeuf, France.

Gallium Nitride and related coumponds materials enlarge the scope of application for opto-electronic and micro-eletronic due to their intrinsic properties. Nevertheless some issues remain, in particular linked to the substrates and, therefore the hetero-epitaxy of GaN based structures, which have a strong limiting impact on final devices performances and cost. We have focused in this work on the compromise between cost and thermal behaviour which is one of the major issue for GaN based power RF device and circuits. During last tree years, results have been reported identifing GaN / AlGaN HEMT as an emerging industrial solution for high power devices [1,2]. Industrialization of such new devices is mainly limited by cost issues and reliability aspects, which depends for the major part on the choice of the epitaxial substrates. Actual limited choices are bulk SiC substrates and Si substrates This paper reports recent results obtained on engineered substrates (up to 4 inches) designed and built by Smart Cut™ technology. Different multi-layered composite substrates were already studied for GaN application like SiCOI structure [3]. This promising engineered substrates has been tested for the growth of AlGaN / GaN HEMT structures by MBE [4]. These first experiments have demonstrated the interest of the Smart Cut™ technlogy and its compatibility for GaN epitaxy. Versatility of the Smart Cut™ technology allow us to introduce a second generation of engineered substrates : Si (111) thin film bonded onto polycrystalline SiC substrate. This new structure is called SopSiC. This engineered substrates combine the capacity to grow state of the art HEMT structure onto Si (111) crystal as seed layer with, at the same time, improved thermal beavhiour compared to bulk Si due to the poly-critalline SiC thermal porperties. Resulting GaN HEMT structures are expected to sustain much higher power levels without performance degradation due to self-heating effect. First step of this work has been the design of the engineered substrates. Simulation results presented here were correlated with experimental measurement and show that SopSiC solution brings strong improvement compared to bulk Si and only a slight degradation is anticipated for thermal behavior compared to bulk SiC. Furthermore, first MBE growth tests of AlGaN / GaN HEMT have been successfully obtained on 100 mm SopSiC substrates. Grown layers exhibit excellent morphology, structural quality and electrical behavior, as good as the ones obtained on bulk silicon. We will present detailed results of characterization performed on the obtained layers (AFM, X-Ray diffraction, carrier sheet density measurement, C(V) measurement, etc.). [1] W.E. Sutton and al. 11th GaAs Symp. (2003) [2] D.C Dumka and al. Elec. Lett. (2004) Vol40 No16 [3] L. Di Cioccio and al. Mat. Sci. And Eng. B Vol46 (1997), p349 [4] H. Larheche and al. Mat. Sci. Forum, Vol 457-460 (2004), p1621

FF28.6
Growth of c-GaN Films on the Nitridated β-Ga_2O_3Substrates Using RF-MBE. Tsutomu Araki[1], Chiharu Morioka[1], Junichi Wada[1], Keisuke Fujiwara[1], Hiroshi Minami[1], Shigeo Ohira[2], Norihito Suzuki[2] and Toetsu Shishido[3]; [1]Dept. of Photonics, Ritsumeikan Univ., Kusatsu, Shiga, Japan; [2]Nippon Light Metal Co, Kambara, Shizuoka, Japan; [3]Institute for Materials Research, Tohoku University, Sendai, Miyagi, Japan.

We have shown that nitridation of β-Ga_2O_3 by exposure to ECR nitrogen plasma successfully resulted in the formation of cubic GaN (c-GaN) layers on the surfaces of β-Ga_2O_3 single crystalline [1]. These results suggest that β-Ga_2O_3 substrates might be a good candidate for homoepitaxial growth of c-GaN. In this paper we report on the growth of c-GaN films on this nitridated β-Ga_2O_3 substrates using RF-MBE. Prior to growth, the β-Ga_2O_3 substrate was thermally cleaned at 700°C. Then, nitridation was carried out at 600°C for 1 hour by ECR nitrogen plasma. A microwave power and a nitrogen gas flow rate were kept constant at 300 W and 10 sccm, respectively. Subsequently, GaN was grown at 700°C for 1 hour by RF-MBE. Ga cell temperature, RF-power and a nitrogen gas flow rate were kept

constant at 880°C, 330 W and 2 sccm, respectively. In order to evaluate the crystallinity of the GaN films, the following characterizations were made. The c-GaN/β-Ga_2O_3 surfaces before and after the growth of GaN films were monitored by in situ reflection high-energy electron diffraction (RHEED) technique. The crystalline structure of the GaN films was investigated using X-ray diffraction (XRD). In-plane XRD with low angle X-ray incident and ϕscan measurements were used to investigate the epitaxial relationship between the GaN films and the substrate. The structural and morphological characteristics of the GaN films were probed by cross-sectional high-resolution transmission electron microscopy (XTEM), and selected area electron diffraction (SAD). The cathodoluminescence (CL) measurement was also performed. RHEED patterns before the growth of GaN films showed (001) oriented single crystalline c-GaN formed on the surface of β-Ga_2O_3 substrate by nitridation. RHEED patterns after the growth of GaN films exhibited that the c-GaN film was homoepitaxialy grown on the c-GaN/β-Ga_2O_3 substrate. A peak of (002) c-GaN was mainly detected from XRD ω-2θ scan of RF-MBE grown GaN film at 700°C, and the ϕ scan revealed a four-fold symmetry, indicating that the formation of (001) oriented single crystalline cubic GaN growth. Epitaxial relationship between c-GaN and β-Ga_2O_3 determined by SAD is (001) c-GaN // (100) β-Ga_2O_3, [110] c-GaN // [010] β-Ga_2O_3 and [1-10] c-GaN // [001] β-Ga_2O_3. However, XTEM observation of the interface at c-GaN/nitridated β-Ga_2O_3 demonstrated presence of both cubic and hexagonal regions of GaN. Inclusion of hexagonal GaN phase was increased with the increase in the growth temperature to 800°C due to the unstable feature of c-GaN thermodynamically. In summary, it was found that single crystalline c-GaN was predominantly grown on the nitridated β-Ga_2O_3 substrate under controlled growth temperature, implying a successful homoepitaxial c-GaN growth for the first time. [1] Wada et al., Extended Abstracts (The 65th Autumn Meeting, 2004), The Japan Society of Applied Physics, 278 (2004).

FF28.7
Microstructural, Optical and Elastic Properties of ScGaN Thin Films. Michelle A. Moram[1], Timothy B. Joyce[2], Paul R. Chalker[2], Zoe H. Barber[1] and Colin J. Humphreys[1]; [1]Dept. Materials Science and Metallurgy, University of Cambridge, Cambridge, United Kingdom; [2]Dept. Materials Science and Engineering, University of Liverpool, Liverpool, United Kingdom.

Epitaxial cubic and hexagonal ScGaN films (having a very close lattice match to GaN) were grown across a wide composition range using ammonia-molecular beam epitaxy, both on silicon substrates and on high quality GaN/Al_2O_3 templates (grown using metal-organic chemical vapour deposition). The microstructure of the films (including in-plane orientation, mosaicity, crystallinity and compositional stability) was determined in detail using x-ray diffraction (XRD) reciprocal space maps, XRD pole figures, atomic force microscopy (AFM) and transmission electron microscopy (TEM). Trends in these properties were related to variations in composition, crystal system and growth conditions. Poisson's ratio, Young's modulus, the thermal expansion coefficient and the stress-free lattice parameter were determined using high-resolution XRD on a series of stressed samples. Optical properties of the films were also investigated, including the band gap (ranging from 2.24 eV to 3.40 eV), the refractive index and the dielectric constant. It is confirmed that Vegard's Law applies to this alloy system. The results of some preliminary photoluminescence and electrical measurements are also reported. These fundamental data allow thus allow the suitability of this novel material for use in GaN-based light-emitting devices to be assessed.

FF28.8
In-situ x-ray studies of $In_xGa_{1-x}N$ growth by MOCVD. Fan Jiang[1], A. Munkholm[2], S. K. Streiffer[1], R.-V. Wang[1], Carol Thompson[1] and G. B. Stephenson[1]; [1]Materials Science Division & Center for Nanoscale Materials, Argonne National Lab, Argonne, Illinois; [2]Lumileds Lighting, San Jose, California.

One of the fundamental issues in the continued development of high performance LEDs is to understand the incorporation of In during growth of $In_xGa_{1-x}N$. Increasing internal quantum efficiency will require optimizing the growth conditions to achieve high In incorporation and crystal quality, and understanding the mechanism and the role of phase separation. Observation of the atomic-scale processes in the vapor, surface, and film during metal-organic chemical vapor deposition (MOCVD) will be key to achieving these goals. Our approach is to use x-ray techniques as in situ probes of MOCVD growth of $In_xGa_{1-x}N$. We have developed a unique facility at the Advanced Photon Source that incorporates an MOCVD system on a synchrotron beamline for real time x-ray scattering and fluorescence studies during growth. Effects of growth parameters such as vapor composition, flow rate, and substrate temperature on film composition, surface structure, growth rate and mode, surface morphology, strain state, and degree of phase separation can be directly and comprehensively explored. We will present our initial results using in situ x-ray techniques to understand In incorporation mechanisms during $In_xGa_{1-x}N$ growth.

FF28.9
Real-Time X-Ray Studies of Ga Adsorption and Desorption on Sapphire and GaN Surfaces. Ahmet S. Ozcan[1], Yiyi Wang[1], Gozde Ozaydin[2], Karl F. Ludwig[1], Anirban Bhattacharyya[3], T. D. Moustakas[3] and D. Peter Siddons[4]; [1]Physics, Boston University, Boston, Massachusetts; [2]Aerospace and Mechanical Engineering, Boston University, Boston, Massachusetts; [3]Electrical and Computer Engineering, Boston University, Boston, Massachusetts; [4]National Synchrotron Light Source, Upton, New York.

Real-time grazing-incidence small-angle x-ray scattering (GISAXS) was employed to study the adsorption and desorption of Ga on c-plane sapphire and GaN surfaces. The experiments were carried out at a new in-situ surface characterization facility developed at the X21 beamline of the National Synchrotron Light Source at Brookhaven National Laboratory. The facility utilizes a removable UHV x-ray chamber equipped with a commercial Ga effusion cell as well as other characterization equipment. In these experiments the sapphire and GaN surfaces were held at constant temperatures ranging from 720 C to 780 C during brief exposures to Ga vapor from the effusion cell. The surface morphology evolution was monitored during initial adsorption and subsequent desorption in real-time using a position sensitive x-ray detector. The GISAXS studies showed that longer periods of Ga adsorption result in the formation of nano-scale droplets on the surface, which are laterally correlated and coarsen in time. Desorption rates were also monitored for the two surfaces.

FF28.10
Room Temperature Layer-by-layer Epitaxial Growth of GaN on ZrB_2. Yuuji Kawaguchi[1], Atsushi Kobayashi[1], Jitsuo Ohta[1,2] and Hiroshi Fujioka[1,2]; [1]Institute of Industrial Science, The University of Tokyo, Tokyo, Japan; [2]Kanagawa Academy of Science and Technology, Kawasaki, Japan.

We have succeeded in layer-by-layer epitaxial growth of GaN on nearly lattice matched ZrB_2 substrates at room temperature (RT) with the use of pulsed laser deposition (PLD). ZrB_2 has been regarded as a promising candidate for epitaxial growth substrates of GaN because the mismatches in the lattice constants and the thermal expansion coefficients are as small as 0.6 % and 5 %, respectively. However, growth of GaN on ZrB_2 with conventional growth techniques such as MBE or MOCVD suffer from formation of thick ZrB_xN_{1-x} interfacial layers due to their high growth temperatures. To solve this problem, we have tried to reduce the growth temperature of GaN on ZrB_2 with the use of PLD [1,2] that helps to enhance the surface migration of the precursors of GaN on the substrate surfaces. After the surface treatment with HF solution[3], ZrB_2 substrates were loaded into an UHV-PLD chamber and annealed at 1000°C for 60 minutes. A Ga metal target (99.9999 % purity) was ablated by a KrF excimer laser (λ = 248 nm, τ = 20 ns) with the energy density around 3.0-5.0 J/cm^2 and the ablated species were deposited onto the substrate placed at 5 cm away from the target. During the growth of GaN, a radio frequency (RF) plasma radical generator was operated at a N_2 pressure of 8×10^{-6} Torr and an input power of 320 W to supply active nitrogen species. After the UHV annealing, ZrB_2 surfaces have shown a $\times$2-reconstructed streaky RHEED pattern, which indicates that the surface was well cleaned with this process. With XPS measurements, we have also confirmed that native oxide layers on ZrB_2 surfaces were removed by the UHV high temperature annealing. RHEED observations have revealed that GaN grows epitaxially with the layer-by-layer mode even at RT and the surfaces of the films are atomically flat. We have found that the intermixing reactions at the GaN/ZrB_2 heterointerfaces, which have been the most serious problem for this system, are well suppressed in the case of RT growth. Electron backscattered diffraction (EBSD) measurements have revealed that the tilt angle and the twist angles of the RT GaN are 0.23° and 0.24°, respectively, even at a film thickness of as thin as 20 nm. The fact that RT GaN shows quite high crystallinity from the early stage of the film growth can be attributed to the small lattice mismatch of this system. These results indicate that the use of RT growth technique and ZrB_2 substrates solves two major problems with heteroepitxial growth of GaN; mismatches in the lattice constants and the thermal expansion coefficients. REFERENCES: [1] J. Ohta *etal.*, Appl. Phys. Lett. **83**, 3060 (2003). [2] A. Kobayashi *etal.*, Jpn. J. Appl. Phys. **43**, L53 (2004). [3] R. Armitage and J. Suda, IWN04, B6.4, July 2004. ACKNOWLEGEMENTS: The authors thank Prof. J. Suda and Dr. R.Armitage of Kyoto University for the fruitful discussion on the surface treatment of ZrB_2. They also thank Kyocera Corporation for the supply of the ZrB_2 substrates.

FF28.11
Epitaxial growth of group-III nitrides on single crystal Fe

substrates. Koichiro Okamoto[1], Shigeru Inoue[1], Nobuyuki Matsuki[2], Taewon Kim[2], Masaharu Oshima[3] and Hiroshi Fujioka[1,2]; [1]Institute of Industrial Science, The University of Tokyo, Tokyo, Japan; [2]Kanagawa Academy of Science and Technology (KAST), Kawasaki, Japan; [3]Department of Applied Chemistry, The University of Tokyo, Tokyo, Japan.

Epitaxial growth of group III nitrides on single crystal metal substrates should be attractive for various applications such as film bulk acoustic resonators (FBARs) and high power light emitting devices. However, it is extremely difficult to fabricate this structure with conventional nitride growth techniques such as MOCVD or MBE due to serious interface reactions between the films and substrates. We have recently found that the use of pulsed laser deposition (PLD) allows us to reduce the growth temperature of GaN dramatically and to suppress interface reactions between GaN and the substrates. [1,2] In this presentation, we will report on the first epitaxial growth of AlN and GaN films on single crystal Fe substrates by PLD. AlN and GaN were grown on single crystal Fe(110), (100), and (111) substrates with a UHV-PLD apparatus with a background pressure of 5.0×10^{-10} Torr. KrF excimer laser pulses (λ=248nm, τ=20ns) ablated a ceramic AlN target and a Ga metal target with an energy density of approximately 1-5 J/cm^2. Characterization of the samples was performed using RHEED, HRXRD, Electron Backscattered Diffraction (EBSD), GIXR, AFM, and XPS. Just before the growth, all the substrates showed sharp streaky RHEED patterns, which indicates that UHV annealing effectively removes the native oxides on the Fe surfaces. This surface reduction by UHV annealing was also confirmed by XPS measurements. We grew AlN on the clean Fe surfaces at low substrate temperatures and found that the AlN (0001) grows on Fe(100). However, we also found that this film contains 30° rotated domains due to the four-fold rotational symmetry of this substrate. Although we expected better crystalline quality for AlN grown on Fe (111) because of the three-fold rotational symmetry, it turned out that the crystallinity is quite poor. EBSD characterization revealed that c-axis of the AlN films on Fe (111) is randomly oriented. On the other hand, AlN films grown on Fe(110) substrates showed a sharp diffraction pattern, which indicates the growth of high quality AlN. Epitaxial relationship for this system turned out to be AlN[11-20] // Fe[001] and AlN[10-10] // Fe[-110]. GIXR measurements revealed that the intermixing reactions at the AlN/Fe heterointerfaces are fully suppressed in the case of PLD growth. We also grew GaN on the AlN/Fe(110) structure. The RHEED pattern for GaN on this structure was sharp streaks. We found that tilt angle and twist angle of GaN deduced from EBSD analysis are as small as 0.221° and 0.293°, respectively. These results indicate that the use of PLD makes it possible to grow high quality group III nitrides on single crystal Fe.
REFERENCES : [1] J. Ohta *etal.*, Appl. Phys. Lett. **83**, 3060 (2003). [2] A. Kobayashi *etal.*, Jpn. J. Appl. Phys. **43**, L53 (2004).

FF28.12
p-Type Doping of InGaN Films Grown by Molecular Beam Epitaxy. Wei Li[1], Theodore D. Moustakas[1], Lin Zhou[2] and David J. Smith[2]; [1]ECE, Boston University, Boston, Massachusetts; [2]Arizona State University, Tempe, Arizona.

The p-type doping of III-nitrides binary compounds and their alloys is still one of the most challenging problems in the field. The successful p-type doping of InGaN alloys can lead to new device applications, such as tandem solar cells involving several InGaN pn junctions and bipolar junction transistors with p-InGaN as the base. In this paper, we present our studies of Mg-doped InGaN films with various InN mole fractions. The InGaN films were grown on (0001) sapphire substrate by RF-plasma assisted MBE. Prior to the growth of the InGaN films, the substrates were first coated with approximately 100nm Ga-polar GaN. The Mg concentration in the films was varied by changing the Mg effusion cell temperature from 200 to 300C. The structure and surface morphology of the films were investigated by in-situ RHEED measurement, and ex-situ SEM, AFM, X-ray diffraction and TEM. The transport coefficients were determined by Hall measurements and the optical properties by cathodoluminescence measurements. The RHEED studies indicate that the undoped InGaN films as well as ones doped with low Mg concentration undergo 3x1 surface reconstruction, while those grown with high Mg concentration show unreconstructed diffraction patterns. Etching studies in KOH indicate the films are group-III polar, consistent with the polarity of GaN template. The undoped films and those doped with low Mg concentration were found to have atomically smooth surfaces, while those grown with high Mg concentration were found to have rough and faceted surfaces. Correspondingly, the resistivity of the films was found to increase over many orders of magnitude as the Mg concentration increases. The best resistivity we have obtained so far equals to 0.6 (Ohm-cm), with carrier concentration of 1x1018cm-3 and mobility of 4 cm2/Vs. The undoped and the p-type doped InGaN films with low Mg concentration show strong room temperature CL spectra while films doped with high Mg concentration don't show room temperature cathodoluminescence.

FF28.13
Investigation of Compensation in Be-doped Gallium Nitride Grown by Molecular Beam Epitaxy. Kyoungnae Lee[1], Brenda VanMil[1], Thomas H. Myers[1], Andrew Armstrong[2], S. A. Ringel[2], M. Rummukainen[3] and K. Saarinen[3]; [1]Physics, West Virginia University, Morgantown, West Virginia; [2]Department of Electrical Engineering, Ohio State University, Columbus, Ohio; [3]Laboratory of Physics, Helsinki University of Technology, HUT, Finland.

It is difficult to obtain p-type conductivity in beryllium-doped gallium nitride. Even when the material exhibits p-type conductivity, it tends to be highly compensated. Beryllium-doped gallium nitride samples grown by molecular beam epitaxy were investigated using deep level optical spectroscopy (DLOS), photoluminescence (PL), and positron annihilation spectroscopy (PAS) in connection with an annealing study in an attempt to correlate compensation and PL features with microscopic defects. Interestingly, both DAP PL and a DLOS indicate an energy level that if interpreted as an acceptor would yield an optical activation energy of beryllium in gallium nitride of about 100meV. These signatures are missing in all as-grown gallium-polar gallium nitride doped with beryllium at levels below 2x1014 cm-3. Upon annealing in pure nitrogen or forming gas, the samples clearly exhibit the DAP at 3.38 eV associated with a shallow Be acceptor, but the samples remain semi-insulating. Interestingly, all nitrogen-polar as-grown samples exhibit the DAP emission at 3.38eV. We will discuss more about the effect of annealing on the apparent optical activation of beryllium and the shift of the photoluminescence peak. DLOS and PAS studies suggest that gallium vacancies and/or gallium-related vacancies are related to compensation in beryllium doped gallium nitride samples. For heavy beryllium doped gallium nitride, there is a correlation between PL at 2.3-2.4eV and a beryllium-related deep acceptor complex. This is supported by PAS studies and DLOS studies. Additionally, there is a correlation between donor-acceptor pair (DAP) at 3.38eV, beryllium concentration, and yellow-red photoluminescence at 2.0 or 2.2eV. This work was supported by ONR Grants N00014-02-1-0974 and N00014-01-1-0571, both monitored by Colin E. C. Wood.

FF28.14
Characteristics of GaN Epitaxial Films Grown at Room Temperature on Various Lattice Matched Substrates. Hiroshi Fujioka[1,2], Jitsuo Ohta[1,2], Atsushi Kobayashi[1] and Shigeru Inoue[1]; [1]Institute of Industrial Science, The University of Tokyo, Meguro-ku, Tokyo, Japan; [2]Kanagawa Academy of Science and Technology, Takatsu-ku, Kawasaki, Japan.

In this presentation, we will discuss characteristics of GaN films grown at room temperature on various nearly lattice matched substrates such as ZnO (000-1), Hf (0001), and (MnZn)Fe2O4 (111). It is well known that the large lattice mismatch between GaN and sapphire, which is the most commonly used substrate, causes a high density of structural defects in the GaN films. To solve this problem, the use of nearly-lattice-matched substrates has been highly requested. ZnO (000-1), Hf (0001), and (MnZn)Fe2O4 (111) have been regarded as promising candidates for epitaxial growth substrates of GaN because the mismatches in the lattice constants are quite small. However, growth of GaN on these materials with conventional growth techniques such as MBE or MOCVD suffers from formation of thick interfacial layers due to their high growth temperatures. To solve this problem, we tried to grow GaN at room temperature (RT) with the use of PLD[1,2] that helps to enhance the surface migration of the precursors of GaN on the substrate surfaces. ZnO (000-1), Hf (0001), and (MnZn)Fe2O4 (111) were loaded into an UHV-PLD chamber with a background pressure of 5.0x10-10 Torr and annealed at 1000 °C. After the reduction of the substrate temperature to RT, a Ga metal target (99,9999 % purity) was ablated by a KrF excimer laser (λ=248 nm, t =20 ns) with the energy density around 4.0 J/cm2 and the ablated species were deposited onto the substrate placed at 5 cm away from the target. During the growth of GaN, a radio frequency (RF) plasma radical generator was operated at a N2 pressure of 8x10-6 Torr and an input power of 320 W to supply active nitrogen species. Characterization of the heterointerfaces and the structural properties of GaN films were performed with RHEED, high resolution XRD, GIXR, and AFM. RHEED patterns for the RT-grown GaN films on these substrates showed clear streaks, which indicates that high quality GaN grows epitaxially with flat surfaces even at RT. The fact that RHEED intensity shows clear oscillation leaded us to conclude that RT-GaN grows in the typical layer-by-layer mode. AFM observations revealed that the surfaces of RT-GaN are atomically flat and often show clear straight steps. We have also tried to use RT-GaN as a buffer layer for GaN grown at 730°C. We confirmed that clear stepped and terraced structures of RT-GaN on ZnO remained even after annealing at a substrate temperature of 730°C. The FWHM values of (0002) and (20-24) XRCs for GaN grown with this technique are 99 arcsec and 284 arcsec, respectively. These results indicate that the room temperatur epitaxial growth technique is quite promising for

the improvement of the GaN crystalline quality. REFERENCES: [1] J. Ohta et al., Appl. Phys. Lett. 83, 3060 (2003). [2] A. Kobayashi et al., Jpn. J. Appl. Phys. 43, L53 (2004).

SESSION FF29: Poster Session: HVPE
Chairs: Leah Bergman and Nicolas Grandjean
Thursday Evening, December 1, 2005
8:00 PM
Exhibition Hall D (Hynes)

FF29.1

What Makes a Good Substrate for HVPE Growth of GaN?
C.E.C. Dam, A. P. Grzegorczyk, P. R. Hageman and P. K. Larsen; Exp. Solid State Physics III, Institute for Molecules and Materials, Radboud Univeristy Nijmegen, Nijmegen, Netherlands.

The main problem obstructing the growth of GaN devices is the absence of native, or at least lattice matched, substrates. One option to overcome this problem is to use Hydride Vapor Phase Epitaxy (HVPE) to grow thick GaN layers. After removal of the substrate these layers can be used as quasi-substrates. Substrates obtained in this way are slowly becoming commercially available. HVPE growth of GaN is a complicated process because many factors contribute to the resulting quality of the grown layers. As a start reactor design, carrier gasses and precursors are very important in obtaining good quality layers. However, after these aspects have been optimized still many things can be varied. We found that the quality of the GaN layers grown by HVPE depends strongly on the choice of substrate. Frequently used substrates are sapphire and SiC. For growth on these foreign substrates intermediate layers are needed to accommodate lattice mismatch and thermal mismatch in order to obtain reasonable quality GaN. For the experiments described here MOCVD grown templates (nucleation layer + buffer layer) are used. Recently our group described a new process for MOCVD growth of GaN on sapphire via a new type of a nucleation layer. [1] A Gallium Treatment Step (GTS) was included in the growth process; with the right conditions it resulted in compressively strained GaN buffer layers. These templates were used for HVPE growth. We found that these substrates are very well suited for HVPE growth of thick, crack-free GaN. In varying the conditions for the GTS we found that the properties of the MOCVD template are very critical to the outcome of the HVPE experiments. In the MOCVD process the growth conditions (thickness and gas phase composition) were varied for both the nucleation and buffer layers of the MOCVD template in the optimization for HVPE growth. We will present data showing the impact of the MOCVD process on the quality of the grown HVPE layer. XRD, defect selective etching and optical micrographs are used to characterize the HVPE layers. With the new templates we are able to grow (at least) 100 μm thick, crack-free GaN layers with low ($<10^8$ cm^{-2}) dislocation density on sapphire. [1] Influence of Sapphire Annealing in Trimethylgallium Atmosphere on GaN Epitaxy by MOCVD, A.P. Grzegorczyk, P.R. Hageman, J.L. Weyher and P.K. Larsen, Journal of Crystal Growth (in press)

FF29.2

Depletion Effect and Crystalline Perfection of the Thin GaN and AlN Epitaxial Layers. Nikolai N. Faleev[1], Mark Holtz[1] and Henryk Temkin[1]; [1]ECE, University of Delaware, Newark, Delaware; [2]Physics, Texas Tech University, Lubbock, Texas; [3]ECE, Texas Tech University, Lubbock, Texas.

Despite extensive research into crystal growth, the epitaxial growth of GaN and AlN on mismatched substrates remains a critical problem in III-N development. Lattice mismatch with commonly used sapphire and silicon carbide substrates leads to abundant generation of point defects on the growth surface. These are generally transformed into extended crystalline defects in the volume of epitaxial layers with typical average density in the layer over 1010 cm-2. In spite of strong deterioration of the growing surface, a 20-50 nm thick intermediate layer is enough to transform the growth from hetero- to homoepitaxial mode. As a result, initial lattice mismatch, as the main growth-perturbing factor, significantly decreases. Under ideal stoichiometry growth conditions a significant diminution of the density of extended defects results in the layer. In thin GaN layers ($<$ 0.6 micron), grown by HVPE on SiC(0001), the density of the threading dislocations is found to be $\sim$ 1 - 4*107 cm-2 [1]. In thin ($<$ 0.3 micron) AlN layers, grown by MBE on Sapphire(0001) substrates, the best data is from layers with threading dislocation density 2*105 cm-2. The density of edge dislocations in the main part of these layers is negligible. To explain this phenomenon we have suggested a model, based on the fundamental rule of point defects, generated on the growth surface, their diffusion and structural transformation to dislocations and dislocations walls. We also suggest a depletion (getter) effect based on ability of threading dislocations, located in the intermediate layer, to attract a lot of diffused point defects to complete structural transformation of these dislocations. It was found that depletion effect properly works until the thickness of the layer (i.e. the distance from the growth surface to the intermediate layer) is less than the diffusion length of point defects. After that the density of extended crystalline defects in the main part of these layers increases up to saturation level, determined by the stoichiometry of growth conditions [1]. 1. N. Faleev, et al., submitted for publication.

FF29.3

Thick AlN and AlGaN Layers Grown by HVPE.
Alexander S. Usikov, Vitali A. Soukhoveev, Oleg V. Kovalenkov, Vladimir A. Ivantsov, Alexander L. Syrkin and Vladimir A. Dmitriev; TDI, Inc., Silver Spring, Maryland.

AlN and AlGaN layers grown by HVPE on sapphire and SiC substrates are promising template substrates for advance device applications including blue and UV LEDs, UV detectors, and high power HEMTs. In this paper we report on cracks-free AlN and AlGaN layers grown by novel stress-control HVPE technology. The growth processes were carried out on a multi-wafer home built HVPE unit, at atmospheric pressure, in a hot wall quarts tube reactor with a resistively heated furnace. Ammonia (NH3) and hydrogen chloride (HCl) were used as active gases and argon served as a carrier gas. HCl was passed over Al source to form gaseous aluminum chlorides. The growth conditions were maintained in such a way to obtain growth rates in the range from 0.2 to 3.0 mm/min. The layers were grown on 2- and 3-inch sapphire and SiC substrates. Thickness of crack-free AlN layers exceeds 20 microns and 75 microns for sapphire and SiC substrates respectively. The layers were characterized by x-ray diffraction demonstrating high crystal quality of grown materials. The FWHM for (002) and (102) x-ray rocking curves measured for AlN layers was less than 300 arc sec and 700 arc sec, respectively. AlN and AlGaN layers demonstrated good optical transparency in ultra violet spectrum region. AlN layers grown on sapphire had nearly 100 % optical transparency at 265 nm wavelength. Electrical, structural, and optical properties of thick AlN and AlGaN layers grown by stress control HVPE will be presented. Thickness dependence of defect density and optical properties was studied. Device application of thick AlGaN and AlN layers grown by HVPE will be discussed.

FF29.4

Strain Mapping of Thick HVPE AlN Films using Low Vacuum Cathodoluminescence. Mikhail E. Gaevski, Rakesh B. Jain, Jiawei Li, Arulchakkaravarth Arjunan, Jinwei Yang and M. Asif Khan; Electrical Engineering, University of South Carolina, Columbia, South Carolina.

The maximum layer thicknesses in the heteroepitaxy of high-quality AlN films are severely restricted by the difference in thermal expansion coefficients and lattice mismatch. These mismatches lead to a strong strain resulting in wafer bowing and an eventual film/substrate cracking. In past, room-temperature cathodoluminescence (CL) mapping of GaN and AlGaN, has been used to quantitatively measure the strain distribution over the grown wafer surfaces. However a pre-requisite for this mapping is the availability of films with a good enough quality to yield strong room-temperature luminescence. To date there are no reports of room-temperature strain mapping in high quality single crystal AlN films. In this paper we for the first time present such a study for high quality HVPE deposited AlN films using room-temperature CL mapping. AlN layers with thickness up to 5 μm were grown by HVPE over (0001) sapphire using a MOCVD grown 0.1 μm thick AlN film as a template. The HVPE depositions were carried out in an inverted reactor using Al/HCl and NH3 as the precursors at a growth rate of 5 μm/hr. CL measurements on as grown films were carried out using JEOL 5900 low vacuum SEM with Gatan MonoCL system. Nitrogen gas with pressure ranging from 10 Pa to 50 Pa was used as the ambient for the CL studies. Dependence of the charging effects on nitrogen pressure was also studied. It was found that nitrogen pressure as low as 40 Pa was sufficient to avoid any CL image distortion from the charging. A mosaic structure of AlN films was clearly seen in the CL images with bright spots separated by darker regions. These corresponded to the grains and grain the boundaries, respectively. Our CL imaging technique was fully capable to distinguish and resolve submicron size grains indicating its high spatial resolution. This CL maps also revealed a network of fully and partially overgrown cracks under the relatively smooth top surface of the HVPE AlN films. Monochromatic CL images show a strong dependence of emission intensity on local strain conditions. Less strained regions grown over a buried crack showed strong band-edge emission at 6.018eV. The increase of tensile strain with the distance from the cracks was analyzed through the red-shift of this near band-edge emission peak. The red-shift exceeded 100 meV for 3 μm thick films, which corresponds to a 1 % ($\Delta a/a=0.01$) variation of the lattice parameter and a local stress of about 2 GPa. It was also found that the strain distribution saturates within 10 μm from cracks. The crack network becomes more intense and multileveled with increase of the film thickness and, simultaneously, the value of the average strain

decreases. In this paper the details of the growth and the CL strain mapping of high quality HVPE deposited AlN fims will be presented.

FF29.5
Temperature and Dislocation Density Effects on the Thermal Conductivity of Iron Doped Semi-insulating Gallium Nitride.
Christian Mion[1], John Muth[1], Drew Hanser[2], Edward Preble[2] and Mary Ellen Zvanut[3]; [1]ECE Dept, North Carolina State University, Raleigh, North Carolina; [2]Kyma Technologies, Raleigh, North Carolina; [3]Physics Dept., University of University of Alabama at Birmingham, Birmingham, Alabama.

The performance of III-Nitride high power, high frequency transistors and laser diodes is intimately connected with the ability to dissipate heat from the junction to the substrate. The thermal conductivity was characterized by the three omega method for undoped and doped gallium nitride bulk substrates grown by HVPE from room temperature to 450 K. The thickness of the samples varied from thin film epilayers on sapphire to 2 millimeter thick free standing samples Dislocation density of the substrates was measured by imaging cathodoluminescence, SIMS was used to measure impurity levels of oxygen, hydrogen, silicon, and iron, while carrier concentrations and resistivity were determined from electrical measurements an EPR. Photoluminescence measurements were also performed. A semi-insulating, 2 mm thick iron doped sample had the highest thermal conductivity of 230W/K-m at room temperature. Undoped sample had comparable, but lower thermal conductivities throughout the temperature range from 300-450 K. By comparing these results with previously reported experimental results including those on MOCVD grown GaN free of grain boundaries, we establish an empirical relationship in a compact formula that relates the thermal conductivity of GaN and the dislocation density with three different regimes of low, intermediate, and high dislocation densities. In the high dislocation regime, the thermal conductivity improves significantly with reduction of dislocation densities. As material quality continues to improve it remains to be seen if in the low dislocation density regime, thermal conductivities will approach 300 W/K-m or plateau out near 250 W/K-m. As point defects start to limit the thermal conductivity when dislocation density becomes very low, gallium vacancies are expected to play an increasing role. Iron is postulated to substitute on the gallium site. The indication from this study is that iron doping at concentration of 1018 cm-3 is not limiting the thermal conductivity in the 300-450 0K range.

SESSION FF30: Poster Session: Bulk
Chairs: Leah Bergman and Nicolas Grandjean
Thursday Evening, December 1, 2005
8:00 PM
Exhibition Hall D (Hynes)

FF30.1
Single Crystal GaN Growth from Different Powder Sources.
Huaqiang Wu[1], Phanikumar Konkapaka[1], Yuri Makarov[2] and Michael G. Spencer[1]; [1]School of Electrical and Computer Engineering, Cornell University, Ithaca, New York; [2]Semiconductor Technology Research, Inc., Richmond, Virginia.

The development of GaN substrates will provide the impetus for new device advances and device performance improvements in the III-nitride materials system. In particular low dislocation substrates will help enable high power light emitting diodes and laser diodes development. Different approaches have been developed to grow thick films or boules of GaN, such as: HVPE, high pressure process, sublimation, ammonothermal growth, vapor phase transport and liquid phase growth. In this report, growth of GaN by vapor transport will be the focus. GaN crystals are grown in a dedicated, resistively heated reactor at a temperature about $1050 - 1200^{o}$C and under pressure of 600 Torr. In this approach, gaseous Ga is obtained by decomposing powder source while nitrogen is provided from the dissociation of ammonia gas. The source materials include commercial GaN powder which contains lost of oxygen, high purity GaN powder (>99.9%), Ga_2O_3 powder, mix of Ga_2O_3 and graphite powder, and mix of commercial GaN and high purity GaN powder. From experiments, high purity GaN powder couldn't provide Ga vapor efficiently for GaN growth. Only $\sim 30\mu$m/hr growth rate has been achieved using high purity GaN powder. More than 250μm/hr growth rate has been achieved using other powder sources. This could due to the efficient transport of Ga_2O vapor piece. Graphite is used to help the conversion from Ga_2O_3 into Ga_2O. GaN single crystals grown from different powder source are extensively characterized. X-ray diffraction (XRD), scanning electron microscopy (SEM), transmission electron microscopy (TEM), glow discharge mass spectrometry (GDMS), as well as x-ray topography studies are employed to analyze the structure, composition and defects. The growth mechanism based on the characterizations will be discussed in the presentation. Layers have shown excellent single crystal quality grown using this vapor transport technique. The dislocation densities less than $1\times10^{6}/cm^{2}$have been measured by TEM. Some of the samples' surface morphologies are dominated by spiral growth and V defects. Others of them are free of V-defects. The possible causes for V-defects will be addressed here. A systematic study of the growth rate as a function of growth temperature, III/V ratio and gas flow rate has been undertaken. Results of these measurements as well as prospects for realization of GaN boules from this technology will be discussed.

FF30.2
Effect of the ambient gas during sublimation growth of AlN crystals. Ziad Georges Herro, Dejin Zhuang, Raoul Schlesser and Zlatko Sitar; Materials Science And Engineering, North Carolina State University, RALEIGH, North Carolina.

Proper control over the thermal field during crystal growth is usually one of the prerequisites to obtain high quality crystals. This is of particular importance in the case of sublimation growth of AlN due to the relatively high transport rates and the need for low axial gradients to reduce material losses from the quasi-open crucible. Due to the unavailability of ideal thermal insulation materials compatible with the required, elevated growth temperatures (above 2200 °C), porous graphite insulation appears to be a good choice due to its relatively low cost and ease in machining. In this work, the role of carbon contamination resulting from the use of graphite insulation was investigated experimentally. Usually, N2 is used as an ambient gas, as it is one of the constituents of the Al-N2 system and as it helps to avoid the formation of chemically aggressive, liquid Al, which tends to rapidly deteriorate crucible materials. However, the use of N2 in graphite surroundings typically leads to a carbon-rich environment due to chemical C-N reactions occurring at elevated temperatures. Investigating the viability of other ambient gases is therefore of interest. In this study three sets of experiments were carried out using either pure Ar instead of N2, or mixtures of Ar/N2. These experiments were performed using tungsten crucibles; crystals were grown in an unseeded growth scheme on tungsten caps. X-ray analysis was performed to compare the crystallographic directions of the spontaneously nucleated crystals. Interstitial gas analyses were performed to determine C contamination levels in the crystals growing in varying ambient gas compositions. In the presentation practically viable ratios of Ar/N2 mixtures will be discussed, under particular consideration of the partial pressures of Al(g) and N2(g) for different ambient gas pressures.

FF30.3
Defect Content Evaluation in Single-Crystal AlN Wafers.
Robert T Bondokov[1], Kenneth E Morgan[1], Raj Shetty[1], Wayne Liu[1], Glen A Slack[1], Mark Goorsky[2] and Leo J Schowalter[1]; [1]Crystal IS, Inc., Green Island, New York; [2]Materials Science and Engineering, UCLA, Los Angeles, California.

Aluminum nitride (AlN) offers exceptional properties necessary to explore development of large area substrates for nitride based electronics and photonics. Recent studies on AlN bulk growth using sublimation-recondensation method developed at Crystal IS demonstrated high-quality crystals with low dislocation density and crystallographic uniformity. Diameter enlargement is often associated with extensive defect generation. The goal of this study is to evaluate the origin and distribution of growth defects in AlN bulk crystals. AlN crystals were grown using sublimation-recondensation technique and then sliced into wafers. The defect evaluation in this study was completed using x-ray topography, differential image contrast and polarized light optical microscopy, atom force microscopy (AFM) and etch pit pattern delineation. In addition, we report on optical transparency including deep ultraviolet region. Special attention was paid on crack development and propagation, domain structure emergence, low angle grain boundary distribution, micro-scale inhomogenities as well as dislocation origin and density. The major cause for growth defect occurrence was found to be non-linearity of both axial and radial gradients. The growth induced inhomogenities appeared at higher supersaturations, meager vapor stochiometry control and thermal fluctuations. The residual stresses build into the growing crystal during different stages of growth were to the most extend accountable for domain and low angle grain boundaries generation. It was shown that growth regimes optimization in terms of above mentioned parameters result in lower defect density and improved crystallinity of AlN crystals.

FF30.4
Single Crystal Growth of AlN by Sublimation Method.
M. Miyanaga, N. Mizuhara, S. Fujiwara, M. Shimazu and H. Nakahata; Sumitomo Electric Ind., Ltd., hyogo, Japan.

Aluminum nitride (AlN) single crystal is one of the promising materials for substrate of deep UV optoelectronic devices and high-frequency electronic devices. However, growth of larger size

crystal and further reduction of dislocation density are needed for device application. We have prepared single crystal AlN by a sublimation method and investigated the effect of the thickness of the AlN single crystal on the dislocation density and crystalline quality. AlN single crystals with different thicknesses from 3 μm to 1.5 mm were grown on SiC substrates by a sublimation method. The FWHM of XRD rocking curve of AlN(0002) reflection was as small as 35 arcsec for the sample of 3 μm thickness, which indicates superior crystalline quality. With increasing the thickness of the AlN crystal up to 200 μm, the FWHM became larger, but it significantly decreased with the thickness of 1.5 mm. The density of cracks decreased with increasing the thickness of AlN crystal. These dependences on the thickness could be explained by the calculation results of the stress which is caused by the mismatch of thermal expansion between AlN and SiC at cooling process. TEM observation was also conducted for the AlN crystals. In the vicinity of the AlN/SiC interface, high-density dislocations were observed, however the density decreased rapidly at 1 μm above the interface. The characteristic dislocation of aligned clusters, which presumably results from the large thermal stress, was observed in the middle region of the AlN crystal. The estimated thickness of AlN crystal to be free from cracking and dislocation will be discussed. This work was partially supported by the High-Efficiency Ultraviolet Semiconductor Emitter Project of the New Energy and Industrial Technology Development Organization.

FF30.5
Atomic Force Microscope Study on Native Aluminum Nitride Surfaces. Sandra B. Schujman, Wayne Liu, Nicholas Meyer and Leo J. Schowalter; Crystal IS, Inc., Green Island, New York.

Native aluminum nitride (AlN) single crystal substrates are promising for use in epitaxial growth of III-nitride materials for fabrication of reliable deep UV light emitting and high power RF devices. Furthermore, the single crystals can be cut into different orientations, such as non-polar or pre-determined and specific misorientations, which will open a door for growing device structures with specially desired properties. We have found several novel patterns on different orientation AlN substrates using Atomic Force Microscope (AFM). Aluminum nitride substrates with chemical-mechanical-polishing (CMP) finished surfaces, for a number of different misorientations with respect to the main hexagonal axis, that is, c-, a- and b-axis, show well differentiated structures. The AFM images reveal atomic level closed-loop hexagonal rings, spirals, and mixtures of those two types of structures. We believe the closed-loop rings and spirals are related to edge-dislocations and screw-dislocations, respectively. These structures are mostly seen on the near and on-axis aluminum polar surfaces. Atomic steps are not always visible on the non-polar bare surfaces and for larger deviations from the polar axis (i.e., larger than 5 degrees from the c-axis). One possible explanation for this difference is that due to the stability of the aluminum polarity the etching rate of the substrate during CMP process decreases as the deviation from the (0001) surface decreases. It is also noticed that even though atomic level steps are not always visible on the bare substrate for non-polar and large misorientations from the polar aluminum face, they can be observed after homoepitaxial and heteroepitaxial growth on these orientations. The research results indicate that both substrate orientation and surface treatment play an important role in forming different kinds of surface morphologies.

FF30.6
Crystal Growth and Defect Characterization of AlN Single Crystals. Shaoping Wang[1], Micheal Dudley[2] and Andy Timmerman[1]; [1]Fairfield Crystal Technology, LLC, New Milford, Connecticut; [2]Materials Science and Engineering Department, SUNY at Stony Brook, Stony Brook, New York.

Since bulk GaN single crystals are difficult to produce, AlN single crystal is the best choice of materials suitable for high quality III-V nitride epitaxy. AlN has the closest lattice-match with GaN among all the substrate materials other than GaN itself. In fact, AlN substrates has a better lattice match with III-V nitride epilayers at high Al contents whose lattice constants fall between that of GaN and AlN. Unlike SiC and sapphire, AlN forms continuous solid solutions with GaN, i.e., AlxGa1-xN, because they have the same crystal structure (2H). Thus AlxGa1-xN ternary compounds can be grown pseudo-morphically on AlN substrates, which means that high quality III-V nitride epitaxial materials with low dislocations can be produced on AlN substrates. AlN single crystals can be grown using physical vapor transport (PVT) techniques, based on the pioneer work done by Slack and McNelly [1, 2]. Intense research efforts were made in recent years in developing AlN PVT bulk crystal growth techniques and AlN single crystals of more than 12mm in diameter were demonstrated [3]. But, AlN substrates are still not yet commercially available at present. One of the major difficulties in growing AlN bulk crystals stems from the fact that Al vapor readily reacts with almost all the common refractory crucible materials at high temperatures. The reaction between Al vapor and the crucible/insulation materials not only contaminates the growing AlN crystals significantly, but also severely limits the lifetime of the crucible/insulation setups. Thus, finding a suitable crucible and insulation material system for AlN PVT growth is an essential task in developing a commercially viable AlN PVT crystal growth process. In this investigation, PVT AlN crystal growth experiments are carried out and the purpose of the experiments is to understand the morphology and crystalline quality of PVT AlN crystals grown under different growth environments. AlN single crystals of various sizes and shapes are produced. Surface morphology of the AlN single crystals is studied using optical microscopy and scanning electron microscopy. Selected AlN single crystals are studied using a high resolution X-ray double-crystal diffraction technique and Synchrotron White Beam X-ray Diffraction Topography technique. Defects identified in AlN crystals in this study include dislocations, grain boundaries and inclusions. Preliminary results from the analyses of the PVT-grown AlN crystals will be discussed extensively. References [1] G.A. Slack, T.F. McNelly, J. Crystal Growth 34 (1976) 263. [2] G.A. Slack, T.F. McNelly, J. Crystal Growth 42 (1977) 560. [3] J.C. Rojo, et. al. J. Crystal Growth, 231 (2001) 317-321.

FF30.7
Structural characterization of GaN single crystal layers grown by vapor transport from a gallium oxide (Ga_2O_3) powder source. Balaji Raghothamachar[1], Phanikumar Konkapaka[2], Michael Dudley[1] and Michael Spencer[2]; [1]Materials Science & Engineering, Stony Brook University, Stony Brook, New York; [2]Electrical and Computer Engineering, Cornell University, Ithaca, New York.

Growth by vapor transport is a promising technique for obtaining bulk single crystals of GaN for use as substrates for nitride-based devices such as LEDs, high power FETs and laser diodes. Typically, GaN growth by vapor transport is achieved by Ga transport under a temperature gradient in an ammonia atmosphere from a GaN powder source to a sapphire substrate with a GaN epilayer deposited on it. While growth rates as high as 200μm/hr are obtained, growth slows down considerably due to formation of liquid Ga in the source. Since GaN growth occurs by Ga transport via Ga_2O, a source such as gallium oxide (Ga_2O_3) can also be used along with a reducing substance like carbon (graphite) to obtain Ga_2O and thus, the formation of liquid Ga can be prevented. Using gallium oxide and graphite powders as source, GaN growth has been carried out under different growth conditions. The resultant GaN single crystal layers are characterized by synchrotron white beam x-ray topography (SWBXT) and high resolution x-ray diffraction (HRXRD) to evaluate the structural defect distribution and overall quality. Cross-sections are examined by a combination of optical microscopy, SEM and TEM techniques to investigate defect generation and propagation at the different interfaces. Characterization results will be compared with results from GaN layers grown using GaN powder source and also correlated to the growth conditions in order to optimize growth.

FF30.8
Synthesis of Bulk Aluminum and Indium Nitride by Ammonothermal Techniques. Bunmi Adekore[1], Kelly Rakes[2], Buguo Wang[3], Michael Callahan[2] and Zlatko Sitar[1]; [1]Materials Science and Engineering, North Carolina State University, Raleigh, North Carolina; [2]Sensor Directorate, Air-force Reseach Laboratory, Hanscom, Massachusetts; [3]Solid-State Scientific Corporation, Hollis, New Hampshire.

Ammonothermal Synthesis has been explored as a viable technique for the bulk crystallization of III-Nitrides. Polycrystalline Aluminum Nitride (AlN) and Indium Nitride (InN) crystals were synthesized under reverse gradient solubility conditions in ammono-basic supercritical Ammonia at growth temperatures between 400°C and 550°C for twenty-one days. Scanning electron microscopy revealed hexagonal Aluminum Nitride and Indium Nitride crystals which varied between 100$_\mu$ms to 1500$_\mu$ms in thickness. Energy Dispersive X-ray (EDX) analysis employed to investigate the composition of the AlN and InN crystals, indicated a significant, yet unintentional incorporation of oxygen. Transmission spectroscopy also revealed an approximate bandgap of 0.5eV at 30% transmission for the ammonothermally synthesized Indium Nitride crystals.$2_{\theta-\omega}$ X-ray diffraction measurements also indicated the presence of hexagonal Aluminum Nitride and Indium Nitride crystal planes.

SESSION FF31: Nano
Chair: Oliver Briot
Friday Morning, December 2, 2005
Grand Ballroom (Sheraton)

8:00 AM *FF31.1
MOCVD Growth and Characterization of AlGaInN Nanowires and Nanostructures. Jung Han[1], Arto V Nurmikko[2], S. F. Chichibu[3] and C. Broadbridge[4]; [1]Electrical Engineering, Yale

University, New Haven, Connecticut; [2]Division of Engineering, Brown University, Providence, Rhode Island; [3]Physics, University of Tsukuba, Tsukuba, Japan; [4]Physics, SCSU, New Haven, Connecticut.

Bottom-up fabrication of semiconductor nanostructure is of considerable interest for exploring quantum phenomena and future-generation devices. Employment of so-called "vapor-liquid-solid" (VLS) mechanism of growth renders a unique pathway to one dimensional (1D) semiconductor nanowires that are promising components in nanoscale technology. GaN nanowires have been prepared using techniques such as pulsed laser deposition, near-equilibrium tube-furnace deposition. The employment of atomistic epitaxial tools such as MOCVD is expected to inject exciting degrees of freedom into nanowire device synthesis. In this talk we will discuss the synthesis of AlGaInN nanowires by MOCVD and their characterization. The non-equilibrium nature of MOCVD places stringent restriction on the selection of growth parameters based on kinetic consideration. It was found that nanowires tend to grow along non-polar m- or a- directions. By varying the ratio between TMGa and TMAl in the gas phase, AlGaN nanowires can be synthesized. Study of the spatial distribution (length and density) of nanowire morphology suggests that surface diffusion of adatoms play an important, if not dominant, role in the nanowire growth, in contrast to the existing VLS growth model. The difference in surface diffusion characteristics between Al and Ga adatoms leads to a spontaneous formation of AlGaN coaxial nanowires. Crystallographic alignment of AlGaN nanowires is achieved by selecting the starting crystalline templates conducive to subsequent epitaxial process. Cathodoluminescence study (monochromatic mapping) indicates fiber-like waveguiding effect associated with these aligned nanowires. A new class of horizontal nanowire devices interconnected epitaxially between contact mesas, as well as complex nanowire networks, can be envisioned through a combination of lithography, epitaxial lateral overgrowth, and crystallographically aligned VLS growth. The authors acknowledge the support of DOE NETL and NSF.

8:30 AM FF31.2
Process for Epitaxial Growth of GaN Nanorod Arrays of Varying Diameters on the Same Substrate. Parijat Pramil Deb[1], Vijay Rawat[1], Mark Oliver[1], Eric A. Stach[1] and Timothy D. Sands[1,2]; [1]Materials Engineering, Purdue University, West Lafayette, Indiana; [2]Electrical and Computer Engineering, Purdue University, West Lafayette, Indiana.

The lateral relaxation of lattice misfit strain in heterostructures grown on nanoscale substrates substantially increases the range of lattice misfit and overlayer thickness that can be accommodated without the introduction of extended defects when compared to conventional planar heteroepitaxy. In the case of (In,Ga)N, nanoheteroepitaxy offers the possibility of increasing the maximum InN mole fraction that can be accommodated in quantum confined structures, thereby promising a broader range of emission wavelengths for GaN-based LEDs. To take advantage of this aspect of nanoscale strain engineering for white light emitters or tunable monolithic sources, it will be necessary to develop processes for fabricating arrays of GaN nanorods with spatially varying diameters in specific patterns. In this presentation, we describe a process for attaining control of GaN nanorod dimensions without nanolithography or foreign catalysts. The process yields monocrystalline, vertically aligned and faceted GaN nanorods with diameters ranging from 50 nm to 100 nm distributed in the form of microscale subarrays, each exhibiting monodisperse feature sizes. The process begins with electron-beam evaporation of a 60 nm SiOx film followed by a 1 μm Al film onto a (0001) GaN film. The Al film is subjected to a two-step anodization process resulting in a porous anodic alumina (PAA) film approximately 250 nm in thickness. Pore widening in phosphoric acid is then used to increase the PAA pore diameter. The PAA pore pattern is then transferred into the SiOx film using reactive ion etching. Finally, the alumina template is selectively etched away. The remaining porous silica template defines the positions and diameters of the GaN nanorods grown selectively within the pores by organometallic vapor phase epitaxy. A low V/III ratio along with hydrogen as the carrier gas results in <0001> oriented GaN nanorods with prismatic {1-100} facets, terminated by a cap defined by pyramidal {1-101 } facets. Diameter control of the nanorods is achieved by varying the anodization potential and pore widening time in selected areas of the wafer through photolithography, resulting in controlled variation of nanorod diameter across the wafer. The implications of these nanorod array substrates for studies of strain effects in heteroepitaxy, as well as their potential impact on band engineering in electronic and photonic devices will be discussed. This work was supported in part by the National Science Foundation (ECS-0424161)

8:45 AM FF31.3
High degree of crystalline perfection in spontaneously grown GaN nanowires. Kris A. Bertness[1], A. Roshko[1], A. V. Davydov[2], I. Levin[2], M. D. Vaudin[2], J. M. Barker[1], J. B. Schlager[1], N. A. Sanford[1] and L. H. Robins[2]; [1]Electronics and Electrical Engineering Lab, NIST, Boulder, Colorado; [2]Materials Science and Engineering Lab, NIST, Gaithersburg, Maryland.

We have grown a variety of isolated GaN nanowires using gas-source molecular beam epitaxy (MBE) and characterized their structural and optical properties. The nanowires have demonstrated a number of promising materials characteristics, including low defect density and high luminescent efficiency. Well-separated nanowires formed spontaneously on Si(111) substrates after deposition of a thin AlN buffer layer for growth conditions including low group III flux, high nitrogen flux (with RF-plasma dissociation), and substrate temperatures near 820 °C. These conditions are qualitatively similar to but quantitatively different than conditions reported by other growers for nanostructure growth. Metal catalysts were not used. Typical GaN nanowires were 50 to 250 nm in diameter, maintaining nearly constant hexagonal cross-section for lengths up to at least 6.5 μm, with the central axis parallel to the [0001] crystal direction. X-ray diffraction indicates that the c and a lattice parameters are within 0.01% of the lattice parameters of bulk GaN. TEM revealed the wires to be free of dislocations and stacking faults, although a matrix layer growing at the base of the wires was found to have a high density of basal plane stacking faults. The photoluminescence intensity at 4 K was also similar for nanowire specimens and a free-standing, thick film of HVPE-grown GaN, despite the smaller volume of material in the nanowires specimens. Both photoluminescence and cathodoluminescence spectra at 4 K are dominated by the donor-bound exciton peak near 3.472 eV. Wire growth was accompanied by growth of a base layer that resembled an irregular matrix with deep holes, often with faceted sides. Wires appeared to inhibit the growth of the matrix in their immediate vicinity, most likely by consuming available material. The true nanowires grew perpendicular to the growth substrate with hexagonal cross-sections and frequently terminated in a plane steeply tilted relative to the growth axis. The relatively high uniformity of wire length indicated that nucleation probably occurred early in the growth. Larger structures resembling ribbons, rods, folded ribbons, and v-shaped pairs of rods were also observed growing at angles tilted relative to the substrate. With field-emission scanning electron microscopy (FESEM), we occasionally observed nanowire nucleation on top of the matrix layer or other larger structures. Further details of the correlations between structure and growth parameters will be presented.

9:00 AM FF31.4
Microphotoluminescence studies on single GaN nanocolumns. Kathrin Sebald[1], J. Gutowski[1], N. Thillosen[2], S. Montanari[2], R. Meijers[2], R. Calarco[2], N. Kaluza[2], H. Hardtdegen[2] and H. Lueth[2]; [1]Institute of Solid State Physics, University of Bremen, Bremen, Germany; [2]Institute of Thin Films and Interfaces and Center of Nanoelectronic Systems for Information Technology, Reseach Center Juelich GmbH, Juelich, Germany.

One-dimensional nanostructures have become an exciting, challenging and rapidly expanding research field. Because of the large bandgap of GaN and the structural confinement of charge carriers as well as of light in nanostructures the fabrication of optoelectronic devices with relatively low power consumption is potentially feasible. Moreover, the investigation of one-dimensional nano-scale GaN will contribute to the understanding of fundamental characteristics which underlay the observed optical properties of this material system. Most publications report on the optical properties of an ensemble of GaN nanocolumns (NC). We will present temperature and excitation dependent microphotoluminescence (μ-PL) measurements on single etched and self-assembled grown NCs on two different substrates. For the etched NCs compact GaN samples were grown on Si(111) substrates by plasma-assisted molecular beam epitaxy (MBE) and on α-Al_2O_3(0001) substrates by metalorganic vapor phase epitaxy. The NCs were fabricated by reactive ion etching. The NCs on sapphire possess a density of 1-2*10^9 cm^{-2} with a homogeneous length of $\sim$ 1 μm and a width in the order of 50-70 nm. For the NCs on Si the base-to-tip ratio is much larger. Self-assembled GaN NCs were grown by MBE on Si(111) substrates. They possess a hexagonal shape with a typical diameter, height and density of 50-80 nm, 100-500 nm, and 3-4*10^9 cm^{-2}, respectively. For the μ-PL investigation single NCs were prepared from the ensemble. The optical investigations are carried out by using a temperature variable μ-PL setup. The samples are excited nonresonantly at 3.82 eV. At low temperatures (4 K) the μ-PL spectra are dominated by the photoluminescence signal of the donor-bound exciton (D^0X) at 3.473 eV. The spectral position is independent of the substrate or processing technique as expected for a relaxed system. Predominantly for the NCs on sapphire substrate an emission peak is observed at $\sim$ 3.41 eV which, in coincidence to findings in literature, is attributed to excitons bound to structural defects. The photoluminescence intensity of this emission line differs for the investigated NCs and is in some few cases more pronounced than the D^0X signal. In the case of self-assembled GaN columns on Si a dominant emission line at 3.45 eV is found which is attributed to

excitons bound to Ga interstitial point defects. The assignment of these additional lines to emission processes originating from structural defects is in coincidence with their spectral position being independent of the excitation density. Further, their optical properties are investigated as a function of temperature. The results will be comparatively discussed with respect to the different substrates and processing concepts. These studies on single isolated GaN NCs have shown better resolved structural defect signals compared to measurements on GaN NC ensembles. Thus, this method offers a much better access to the optical properties of such defects.

SESSION FF32: Heterostructures: InGaN
Chair: Andrew Kim
Friday Morning, December 2, 2005
Grand Ballroom (Sheraton)

9:15 AM *FF32.1
Quantum-Confined-Stark-Effect and Polarization Field in Single Quantum Well, InGaN/GaN LEDs. Steven R Kurtz, R. J. Kaplar and D. D. Koleske; Sandia National Laboratory, Albuquerque, New Mexico.

Based on the wurtzite crystal structure, large (MV/cm) polarization-induced electric fields are known to exist in InGaN single quantum wells (SQWs) grown perpendicular to the GaN c-axis, and these fields may impact optical device performance due to the quantum-confined-Stark-effect (QCSE). In general, the QCSE has experimentally been found to be smaller than the theoretical value expected for a coherently strained InGaN QW, and subsequently the InGaN/GaN QW polarization field is often under-estimated as well. In this study, we measure the QCSE in modulation-doped, InGaN/GaN SQW LEDs. The well-behaved capacitance-voltage (majority carrier) characteristics of these devices allow us to unambiguously determine the applied field with bias. With this analysis, we de-couple the QCSE from the QW polarization field and show that although the applied field approaches the opposing QW polarization field theoretical value (i.e., flatband), the QCSE remains too small. $In_xGa_{1-x}N$ SQWs embedded in the n-side of GaN p^+n junctions were grown by metal-organic chemical vapor deposition on sapphire (x $\sim$ 0.11) and SiC (x $\approx$0.14) substrates. The Si modulation doping layer was well-removed (25 nm) from the SQW. Electron density profiles from capacitance-voltage (C-V) measurements revealed a sharp peak associated with charge storage in the SQW, with total QW charge consistent with calculated values. The applied, depletion-layer field at the SQW was determined from the integrated charge (C-V) value. Low-temperature (77 K) photocurrent and electroreflectance spectra were measured versus applied electric field, and SQW features were well-resolved and displayed a blue-shift in reverse-bias due to the QCSE. In a previous study where the Si modulation doping layer was adjacent to the SQW, excess charge was trapped in the QW, and a blue-shift could not be observed in reverse-bias. Using a Schrodinger-Poisson calculation, the QCSE and screened polarization field were obtained for each SQW sample. In the more robust sapphire sample with a calculated polarization field (flatband) of 1.9 MV/cm, a reverse-bias applied field of 1.6 MV/cm was attained. *Despite the applied fields approaching SQW flatband values, the observed Stark-shifts were $\sim$ 50% less than predicted.* In response to several observations, we propose a localized hole picture for InGaN QWs. Hole localization is consistent with the reduced blue-shift, and hole localization does not alter the QW polarization field or the applied field required to achieve flatband. The widespread observation of reduced QCSE indicates that electron-hole QW wave-function overlap is larger than expected, and radical improvement in brightness may not be realized in InGaN QW emitters grown on non-polar substrates. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

9:45 AM FF32.2
Luminescence efficiency of InGaN/GaN quantum wells on bulk GaN substrate. Axel Hoffmann[1], M. Dworzak[1], T. Stempel Pereira[1], G. Fransen[2], S. Grzanka[2], T. Suski[2], R. Czernecki[2], M. Leszczynski[2] and I. Grzegory[2]; [1]Institute of Solid State Physics, Technical University Berlin, Berlin, Germany; [2]Institute of High Pressures - Unipress, Polish Academy of Sciences, Warsaw, Poland.

Due to their outstanding optical properties InGaN/GaN heterostructures are the basis of manifold optoelectronic applications. Nevertheless their application potential is not utilized for a long time yet, and the knowledge of the fundamental processes is far away from a deep understanding. Depending from the layer thickness huge electric fields influence the optical properties of InGaN/GaN heterostructures with a major contribution of strain-induced piezoelectric fields. We present two approaches to suppress the influence of electric fields. Homoepitaxial growth on single GaN crystals reduces the strain and the insertion of Si-doped buffer layers screen the piezoelectric fields. This changes the luminescence efficiency drastically. The results of time-integrated and time-resolved photoluminescence (PL) spectroscopy are presented, performed on InGaN single quantum wells (QW) with widths between 3 nm and 10 nm. The structures were grown by metal organic chemical vapor deposition on sapphire and bulk GaN crystals. This allows us to compare directly the population and recombination mechanisms in thin and ultra-thin QWs on both substrate ma-terials. An absence of a blue shift of the PL at high excitation density and a nearly single-exponential PL decay show the reduced influence of electric fields. Instead of that the luminescence efficiency is strongly influenced by the localization of excitons in a complex potential landscape with localization sites of widely varying depth. An increase of the PL decay times with decreasing detection energy is attributed to carrier transfer processes from shallow to deeper localization sites. Their quantum dot nature is studied by means of spatially resolved luminescence measurements. At low temperatures they prevent carrier/exciton diffusion towards nonradiative recombination centers and are responsible for the high luminescence efficiency. At temperatures above 100 K an enhancement of nonradiative processes could be observed. Radiative and nonradiative life-times were determined.

10:30 AM FF32.3
Quantum Well Network Structures: Investigating Long-Range Thickness Fluctuations in Single InGaN Quantum Wells.
Nicole K. van der Laak, Rachel A. Oliver, Menno J. Kappers and Colin J. Humphreys; Materials Science and Metallurgy, University of Cambridge, Cambridge, United Kingdom.

InGaN quantum wells (QWs) are often grown using a "two-temperature" method with the InGaN grown at a lower temperature than the GaN barrier in order to improve the quality of the GaN barrier. We have observed gross well width fluctuations in two-temperature (2T) InGaN quantum wells. Similar long-range thickness fluctuations have also been reported for InxGa(1-x)N/GaN multiquantum-well LEDs showing bright electroluminescence. It has been suggested that these thickness fluctuations could be attributed to a substantial increase in the optical efficiency compared to LEDs with uniform InxGa(1-x)N/GaN layers[1]. We have grown and characterised a series of InGaN epilayers and quantum well structures with similar PL emission wavelengths (ca.508nm) to determine whether these gross thickness fluctuations may be attributing to the increase in optical efficiency. No well width fluctuations were observed by transmission electron microscopy (TEM) in an unannealed, single-temperature (ST) QW. The average thickness of the QW was determined to be 3.60.$\pm$1nm. By comparison, a similar annealed ST-QW with a post-anneal low temperature cap grown at 710C,°C was found to have gross width fluctuations and a maximum thickness of 3.60.$\pm$1nm. An increase in the PL was observed for the annealed QW compared to the unannealed well, which suggests that the thickness variations may contribute to bright luminescence even when the point defect density in the barrier is significant. Further characterisation was performed by atomic force microscopy (AFM) and high-resolution TEM on an annealed InGaN epilayer. AFM showed a network of interlinking 50-100nm wide strips of InGaN. The strips of InGaN and the elongated pits between them align with the predominant direction of the terraces on the underlying GaN substrate. TEM shows that these strips have distinct {-2112} facets. A temperature-bounced epilayer equivalent to the 2T QW was found to have a similar undulating network structure. Initial STEM-EDX characterisation of the annealed InGaN epilayer suggests that the networks have a higher In content at the edges of the strips compared to their centres. It is thought that the networks form by decomposition of In-rich regions during the anneal, or temperature ramp, leaving behind more stable regions that have a lower In content. These results may provide some insight into the mechanism behind the formation of the gross thickness variations observed in 2T-QWs and LED structures. We speculate that compositional variations occur in strained regions of the well associated with underlying terrace edges or possibly dislocations. Hence In enrichment may occur around the dislocations, and this material may desorb during the temperature ramp or anneal of the InGaN epilayer. Thus, the network structure may confine the excitons away from the dislocations improving PL emission. 1 J. Narayan, H. Wang, J. Ye, S-J. Hon, K. Fox, J-C. Chen, H.K. Choi and J.C.C Fan, *Appl.Phys.Lett* 81, 5 (2002).

10:45 AM FF32.4
Impact of Stress on Indium Incorporation in InGaN Multi-Quantum Wells and Thick InGaN Films.
Daniel D. Koleske, Stephen R. Lee, Arthur J. Fischer, Mary H. Crawford, Michael E. Coltrin, Karen C. Cross and Michael J. Russell; Sandia National Laboratories, Albuquerque, NM, New Mexico.

While the promise for tuning the bandgap from 0.7 to 6.2 eV in the group III nitride materials system exists, achieving wavelengths

greater than 530 nm is difficult due to several factors. These factors include the disparate growth conditions that must be used for In incorporation, especially temperature, and the lattice mismatch between GaN and InGaN alloys. The issue of In incorporation becomes particularly important for light emission at longer wavelengths, where the quantum efficiency is significantly less than for blue LEDs. In incorporation was studied in InGaN multi-quantum wells (MQWs) and InGaN thick films (100 nm) using MOCVD. The In content in the thick films and MQW structure is analyzed using photoluminescence, electroluminescence, x-ray diffraction (XRD) and dynamical diffraction theory. For the high In content thick InGaN films, two XRD peaks are observed in both the (004) and (102) reflections. The first layer is coherently strained and limited to a maximum In content near 0.2 [1], even for growth conditions where the inlet In/(In + Ga) flows are greater than 0.2. The second InGaN layer is strain relaxed and the In content of this layer can easily exceed 0.2. For the thinner (2-3 nm) coherently strained InGaN MQWs the In content did not exceed 0.2 over a wide variety of growth conditions. While these results might imply that not enough In can be incorporated into the InGaN MQWs to produce 525 nm (green) emission, a plot of the MQW In content vs. PL wavelength shows that In contents from 0.15 to 0.20 can produce 475 nm emission and In contents from 0.2 to 0.25 can produce 525 nm emission, suggesting that the effectiveness of the In incorporation and resulting emission wavelength can vary substantially. Details of the In incorporation study will be presented in light of how stress influences In incorporation in blue and green MQWs and LEDs. [1]. S. Pereira, et al., Appl. Phys. Lett. 80, 3913 (2002).

11:00 AM FF32.5
MOVPE Grown InGaN Nano-Islands Studied by STM.
Subhashis Gangopadhyay, Thomas Schmidt, Sven Einfeldt, Tomohiro Yamaguchi, Detlef Hommel and Jens Falta; Institute of Solid State Physics, University of Bremen, Bremen, Germany.

InGaN/GaN quantum well based light emitting diodes and laser diodes have already been commercialized for the blue and ultraviolet spectral region [1]. Employing InGaN quantum dots (QDs) instead of quantum wells may provide further improvement of the device performance since it is expected that this prevents the carriers from non-radiative recombination at crystal defects and that the laser threshold current density is lowered. Although some recent results of metal organic vapor phase epitaxy (MOVPE) [2] and molecular beam epitaxy (MBE) [3] grown InGaN QDs have been reported, still the low density and the broad size distribution of the InGaN islands are predominant problems for device applications. Hence, for a successful growth of InGaN QDs, a better understanding of the underlying growth mechanism is highly desirable. Within this work, MOVPE grown InGaN quantum dots on 3-5 micron thick GaN(0001) templates have been investigated using scanning tunneling microscopy (STM). The samples have been transfered from the MOVPE growth chamber to the STM analysis chamber under dry nitrogen conditions in order to suppress surface oxidation. By varying the growth parameters such as the growth temperature, the In flux, the growth rate, and the III/V flux ratio, different types of InGaN islands are observed. Within the investigated growth parameter ranges, the size of the islands varies from 8-100 nm in diameter and 1-8 nm in height, and In mole fractions are found between 0.2 and 0.5, as determined by x-ray diffraction from thick InGaN layers grown under the respective conditions. For high growth temperatures, large islands with a spiral stacking of disc-like layers, as well as flat-top hexagonal islands and triangular pyramidal islands have been found. The large thermal diffusion promotes island nucleation at defect sites. InGaN decomposition leads to the formation of In droplets, preferentially on top of large islands. Lowering the In flux (N-rich growth), the surface adatom mobility is reduced and hence the island nucleation density is increased. High-density ($10^{12}/cm^2$) arrays of quantum-dot-like InGaN nano-islands of homogeneous size (diameter 8 nm, height 3 nm) and narrow size distribution has been achieved by low temperature growth with reduced In flux. [1] S. Nakamura et al., The Blue Laser Diode, 2nd ed. (Springer, Berlin, 2000). [2] K. Tachibana et al., Appl. Phys. Lett. 74, 383 (1999). [3] C. Adelmann, et al., Appl. Phys. Lett. 76, 1570 (2000).

11:15 AM FF32.6
Near-field photoluminescence spectroscopy of single InGaN quantum dots. Alexander Mintairov[1,2], J. Merz[1], A. Vlasov[2,1], D. Sizov[2], V. Sizov[2], V. Lundin[2], E. Zavarin[2], A. Tsatsul'nikov[2] and N. Ledentsov[2]; [1]EE, University of Notre Dame, Notre Dame, Indiana; [2]Ioffe Physico-Technical Institute, St Petersburg, Russian Federation.

Here we address the question of the nature of sharp emission lines appearing in low-temperature micro-photoluminescence spectra of ultra-thin InGaN layers [1]. Such lines are usually attributed to strong composition fluctuations or quantum dots spontaneously formed in InGaN via strained-induced phase separation or Stranski-Krastanov growth modes. Such strongly localized centers are considered to be responsible for the high brightness of InGaN structures. Here we used near-field scanning optical microscopy operating at temperatures 10-300 K and at magnetic field strengths 0-10 T [2] to study temperature-dependent magneto-photoluminescence of InGaN structures with spatial resolution ~100 nm. The InGaN/GaN and InGaN/InGaN structures, having In content and thickness of InGaN active layers 0.12 and 3 nm, were grown by metallo-organic chemical vapor deposition. Transmission electron microscopy measurements reveal that active layers consist of dense arrays of InN-rich nanodomains with size 2-5 nm [4]. In far-field photoluminescence spectra we observed a strong band centered at 2.5-2.7 eV having half-width 0.1-0.2 eV at 10 K. Using photocurrent measurements and photoluminescence excitation spectroscopy we found that, depending on the growth conditions, the localization energy of the composition fluctuations of InGaN active layer can vary from 0.1 to 0.8 eV. We found that low-temperature near-field photoluminescence spectra of InGaN active layers consist of a few sharp lines and peaks, having half widths ~1 and ~10 meV, respectively. In some structures we also observed broader bands with half width ~70 meV, having weakly resolved fine structure. Using measurements of the diamagnetic shift and scanning experiments we found that the sharp emission lines correspond to single nanodomains (quantum dots) having sizes 2-5 nm and that the broader features correspond to regions (islands) having spatial extend 20-50 nm. We suppose that the islands have complex internal structure and consist of several coupled quantum dots, which results in their broader emission. We observed that above 60 K only broad features remain in the near-field spectra, which gives strong evidence that emission process of InGaN layers at high temperatures are governed by complex composition fluctuations. The work was supported by NATO Collaborative Research Grant CBP.NR.CLG 981516, the W.M. Keck Foundation, and the NSF MRSEC for Nanoscopic Materials Design at the University of Virginia. 1. O. Moriwaki et. al. Appl. Phys. Lett. 76, 2361 (2000); J. W. Robinson, et. al. Appl. Phys. Lett.83, 2674, (2003); R. Seguin et al Appl. Phys. Lett. 84, 4023 (2004); H. Schomig et. al. Phys. Rev. Lett. 92, 106802 (2004). 2. A. M. Mintairov et al Phys. Rev. B 69 155306 (2004). 3. I. L. Krestnikov et al Phys. Rev. B, 66, 155310 (2002). 4. D. S. Sizov et al Proc. Int. Symp. Nanostructures: Physics and Technology, St.Petersburg, Russia, p.296-297 (2005).