SYMPOSIUM EE

Progress in Semiconductor Materials V–Novel Materials and Electronic and Optoelectronic Applications

November 28 - December 1, 2005

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SESSION EE1: Infrared Materials and Devices
Chair: Linda Olafsen
Monday Morning, November 28, 2005
Constitution B (Sheraton)

8:00 AM EE1.1
Atomically Accurate Structure Analysis for Reliable Bandgap Engineering of Strained Layer Superlattices. Haiqiang Yang[1], Ming Zhong[1], Michael B. Weimer[1], Michael E. Flatte'[2], Christoph H. Grein[3], Andrew P. Ongstad[4] and Gerard J. Sullivan[5]; [1]Texas A&M University, College Station, Texas; [2]University of Iowa, Iowa City, Iowa; [3]University of Illinois at Chicago, Chicago, Illinois; [4]Air Force Research Laboratory, Albuquerque, New Mexico; [5]Rockwell Scientific Company, Thousand Oaks, California.

As attempts to exploit the deliberate tailoring of optical transitions in quantum-confined semiconductor structures grow ever more sophisticated, accurate answers to the essential question of the atomic arrangements responsible for the confining potential frequently remain unavailable. Such ignorance forces an unfortunate reliance on bandgap engineering paradigms whose predictive utility is judged against assumed (intended) rather than known (as-grown) structures. We describe a suitably powerful and general method for the complete solution of the relevant structure problem in InAs/GaSb strained layer superlattices whose fundamental bandgap may be tuned anywhere within the mid- to long-wave infrared region of the electromagnetic spectrum. This control, in principle exercised through appropriate design of the respective layer sequences and heterojunction bond types laid down during MBE growth, is, in practice, compromised by a combination of antimony segregation and background incorporation at the arsenide-on-antimonide interface, and by indium segregation at the antimonide-on-arsenide interface. Our approach relies on atomically precise, layer-by-layer compositions derived from cross-sectional scanning tunneling microscopy together with high-resolution x-ray diffraction, and yields a unique, growth-direction-dependent x-ray structure factor that successfully reproduces the variation in (004) satellite peak intensities. A fourteen-band k.p model for the resulting wavelength-dependent optical absorption in a realistic superlattice with segregation-driven interface compromise and non-integer well-to-barrier ratio accurately predicts the abrupt absorption cutoff observed with Fourier-transform infrared spectroscopy. Work supported by the Air Force Research Laboratory, Missile Defense Agency, and National Science Foundation.

8:15 AM EE1.2
Investigation of Interfacial Bond Formation in W-Structured Type-II Infrared Photodiodes using Cross-Sectional Scanning Tunneling Microscopy. Jay Chan Kim[1], Joseph G. Tischler[1], Igor Vurgaftman[1], Jerry R. Meyer[1], Edward H. Aifer[1], Lloyd J. Whitman[1], Chadwick L. Canedy[2,1] and Eric M. Jackson[2,1]; [1]Naval Research Laboratory, Washington, District of Columbia; [2]SFA Inc., Largo, Maryland.

"W-structured" type-II antimonide superlattices (W-SLs) have many advantages for mid-IR semiconductor lasers, including higher differential gain and lower lasing thresholds at higher operating temperature. A typical "W" period consists of a hole quantum well (QW) sandwiched by two electron QWs, which are in turn bounded by barrier layers (e.g. InAs-InGaSb-InAs-AlSb), creating a "W" shaped band structure envelope. Recently we have been investigating ternary (and quaternary) W-SL structures composed of InAs, InGaSb (InGaAsSb), and AlSb (AlInAsSb) layers for use in long-wave and very long-wave infrared photodiodes. Interfaces play an important role in W-SLs since twice as many interfaces are formed in each period compared with two-constituent superlattices such as InAs/GaSb. There are therefore more options available in W-SLs to engineer the interfaces for strain compensation. We use x-ray diffraction to measure the overall strain in the W-SLs, and cross-sectional scanning tunneling microscopy (XSTM) to directly image the atomic-scale structure, including the interfacial bonds, as a function of growth conditions. Difference in the local bond lengths of dissimilar interfaces, e.g. AlAs vs. InSb, results in specific contrast in XSTM images, allowing us to directly identify the interfacial bond types. We have observed that unforced AlSb/InAs interfaces, where both shutters are switched simultaneously in order to create a neutral mix of interfacial bonds, actually consist predominantly of AlAs interfacial bonds, resulting in undesirable strain. In contrast, InGaSb/InAs interfaces are formed as intended. Recently, however, we have found evidence that reducing the As/In flux ratio to near unity can suppress the formation of AlAs bonds without degrading the superlattice. A further benefit appears to be much higher photoluminescence intensity for samples grown under the lower As flux rate. We will discuss the surface science underlying the formation of these interfacial bonds in the presence of varying As background, and the effects on the optical properties of the devices.

8:30 AM EE1.3
High Aspect Ratio Etching Of GaSb/AlGaAsSb For Photonic Crystals. Tron Arne Nilsen[1,2], Anthony Martinez[2], Renato Bugge[1], Luke F. Lester[2] and Bjorn-Ove Fimland[1]; [1]Department of Electronics and Telecommunications, Norwegian University of Science and Technology, Trondheim, Norway; [2]Center For High Technology Materials, University of New Mexico, Albuquerque, New Mexico.

Emitters in the 1.7-2.4 μm (Mid-IR) spectral range are useful for a broad range of applications such as tunable diode laser absorption spectroscopy, free space optical communications and medical surgery. GaSb based emitters are well suited for emission in the mid-infrared range and there is interest to extend the use of photonic crystals (PC) to these materials. PCs are useful for enhancing light extraction from LEDs, PC defect lasers and PC distributed feedback lasers, and photonic band edge lasers. To fabricate PCs in these materials the etch process needs to be well understood. Previous work has been done on dry etching of GaSb and AlGaAsSb [Zhang, et al., JVSTB, 1999] but there is little on the etching of the features required for PCs [Bewley, et al., Solid State Electron., 2002]. The cladding layers of a GaSb-based light emitting structure is typically AlGaAsSb with high Al content (80-90 %). The core consists of low Al content (around 25 %) AlGaAsSb spacers and GaInAsSb quantum wells with high Ga content. PCs in this structure would be formed by either etching partially into the waveguide or all the way through. To have a uniform etch in the latter case, there should be no selectivity between materials. It is assumed the selectivity between GaSb and high Al content AlGaAsSb is the upper bound of the selectivity between low and high Al content AlGaAsSb. PCs designed for emission at 2 μm will usually have holes with a diameter of 500 nm or more depending on lattice and application. The etch depth will typically be between 1μm and 4 μm depending on waveguide design, which makes high aspect ratio etching essential. To achieve good pattern definition, etched sidewalls should to be close to vertical, which will also aid in realistic simulations of the fabricated PCs. Interferometric lithography (IFL) with a 355-nm laser was used for pattern definition and inductively coupled plasma (ICP) consisting of BCl3 and BCl3/Ar gas mixtures was implemented for the etching. Etching experiments were carried out using photoresist (PR), metal and dielectric masks. IFL is well suited for exposing PCs without defects and has an advantage over electron-beam exposure in speed and uniformity over large areas. ICP RIE was used because it allows high density plasmas at low bias voltage. Using a PR mask, etch depths of 1.6 μm and 1.5 μm have been obtained in GaSb and AlGaAsSb (90 % Al), respectively, with near vertical sidewalls. For etch depths around 1 μm vertical sidewalls were obtained. A selectivity of 3 between the PR and GaSb was obtained. For both GaSb and AlGaAsSb aspect ratios of 2.4 were obtained. The selectivity between the two materials was 1.1. Etch rates were found to vary significantly with hole diameter; a reduction from 670 nm to 450 nm resulted in a 15 % drop in etch rate. All results were obtained low DC bias (100-160 V) with etch rates as low as 55 nm/min and 50 nm/min for GaSb and AlGaAsSb, respectively.

8:45 AM EE1.4
3.3-4.3μm High Brightness LEDs. Boris Anatolievich Matveev, Nonna Vyacheslavovna Zotova, Natalia Dmitrievna Il'inskaya, Sergey Arkadievich Karandashev, Maxim Anatolievich Remennyi, Nikolay Matveevich Stus' and Valerii Victorovich Shustov; Physics of Nanoheterostructures, Ioffe Physico-Technical Institute, St. Petersburg, Russian Federation.

Recent years have seen extensive research of the mid-IR (2-5μm) diodes and resonant cavity LEDs as well as conventional LEDs including those with immersion lenses have already broken the 1 mW output power barrier that is necessary for most practical applications. However, curtain applications, such as spectroscopic measurements with gratings and detector system calibration, call for high brightness/apparent temperature rather than high power devices and thus the latter should be free of lenses that magnify the image dimensions. LEDs with flat out-coupling surface emitting at 3.3-3.6μm at room temperature have already shown the ability to simulate the black body heated up to 593 K (positive contrast Δt = 300 K in the 3-5μm band) [Naresh C. Das et al, 2004, V. Malyutenko et al, 2004]. In spite of high output power values that could be found in the literature for the flat uncoated LEDs it is clear that there is still a room for chip design and device performance improvements. Deep mesa that narrows the internal radiation diagram due to the reflections from the inclined mesa sidewalls contribute to the out-coupling enhancement and is thus a useful feature of the high brightness sources. The effect of the above geometrical factor is well known for the InSb (6μm) negative luminescent devices [G.R.Nash et al, 2004] and efficient NIR and visible LEDs. However, to the best of our knowledge there have been no attempts so far to investigate the impact of the mesa dimensions/shape on the output power in a Mid-IR LED with wavelengths shorter than 6 um. We report on double heterostructure (DH) LEDs grown onto heavily doped n+-InAs or undoped n-InAs substrates with 2-7 μm thick active layers formed

from n-InAs (λ=3.3μm) or n-InGaAsSb (λ=3.7μm) or n-InAsSb (λ=4.3μm) and p-InAsSbP claddings (for all LED types). DHs were treated by two stage wet photolithography process that enable us to achieve 10-40μm high sidewalls in a 250μm wide mesas with a 50-210μm wide circular Au-anode in a flip-chip device. Common features of the fabricated LEDs were superluminescence and blue shift of the emission spectrum at 77 K due to dynamic Moss-Burstein effect, current/emission crowding above the anode contact at 300 K and superiority of the negative luminescence power conversion efficiency over the forward one at elevated temperatures (say, at 480 K) due to suppression of the Auger recombination in a depleted active layer. The report will focus on the discussion of experimentally observed impact of several geometrical factors (active layer thickness, mesa and contact diameter and side wall height) on near and far field patterns, emission spectrum and output power including the best achieved light extraction enhancement factor of 2 for the InAsSb LEDs and apparent temperature contrast of Δt=400 K in the 3-5μm band for the InAs LEDs (I=1 A).

9:00 AM *EE1.5

IV-VI Semiconductor Mid-IR Lasers. Patrick John McCann[1] and Yurii Selivanov[2]; [1]Electrical and Computer Engineering, University of Oklahoma, Norman, Oklahoma; [2]P. N. Lebedev Physical Institute, Moscow, Russian Federation.

Mid-IR lasers fabricated from narrow bandgap IV-VI semiconductors are proven devices for molecular spectroscopy applications. Wide single-mode tunability, low waste heat generation, and large spectral coverage from about 1000 cm^{-1} to about 2500 cm^{-1} have allowed development of laser absorption spectroscopy instrumentation for fast and sensitive measurement of specific gas phase molecules. For example, IV-VI mid-IR lasers with emission in the 1900 cm^{-1} spectral range have been used in instruments for real-time measurement of exhaled nitric oxide (eNO). Laser tunability is sufficient for simultaneous measurement of exhaled carbon dioxide (eCO_2), a capability that allows highly accurate determination of eNO concentrations in the low ppb range for assessing airway inflammation in patients with asthma. This presentation will begin with a review of recent progress in the development of liquid-nitrogen-free cryogenic cooling systems for IV-VI mid-IR lasers. Such systems, along with other advances including user-friendly software, have enabled the deployment of IV-VI laser spectrometers in clinical settings for breath analysis research. With established clinical utility in monitoring asthma patients and future potential medical applications ranging from renal and liver function monitoring to detection of cancer, the commercial market for mid-IR lasers promises to expand considerably. Motivated by these important applications, research continues on the development of improved IV-VI lasers, where the primary objective is to fabricate devices with continuous wave (CW) operation at room temperature thus allowing significant reductions in the size and cost of IV-VI laser spectrometers. Recent research results show that maximum CW operating temperature, T_{max}, can be increased significantly by improving active region heat dissipation. Double heterostructure lasers grown by molecular beam epitaxy (MBE) exhibited an increase in T_{max} of 40 degrees (T_{max}=160K to T_{max}=200K) when the low thermal conductivity PbSe substrate was thinned from 180 μm to about 15 μm. Other experimental results involving complete removal of the growth substrate and transferring IV-VI materials to higher thermal conductivity copper also showed significant improvements in active region heat dissipation as determined from epilayer temperatures extracted from measured photoluminescence (PL) spectra [Y. F. Li, P. J. McCann, A. Sow, C. Yao, and P. C. Kamat, "Improvement of Heat Dissipation Through Transfer of IV-VI Epilayers From Silicon to Copper", *IEEEPhotonicsTechnologyLetters* **16**, 2433 (2004)]. Work has also focused on MBE growth of (111)-oriented quantum well structures to achieve a four-level laser design in which electrophonon resonance effects can reduce the threshold for population inversion. Together, these new laser packaging methods and active region materials can help enable the fabrication of widely tunable mid-IR lasers with CW emission at room temperature.

9:30 AM *EE1.6

Mid-IR Interband Cascade Lasers: Progress toward High Temperature Operation. R. Q. Yang, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California.

Mid-IR type-II interband cascade (IC) lasers take advantage of the broken band-gap alignment in type-II quantum wells to reuse injected electrons in cascade stages for photon generation [1] with high quantum efficiency. Unlike intraband quantum cascade lasers, type-II IC lasers use interband transitions for photon emission without involving fast phonon scattering, making it possible to significantly lower the threshold current density. Also, type-II IC lasers can have a wide wavelength tailoring range that is less limited by the conduction-band offset on the short wavelength side. Theoretical calculations [2, 3] projected the feasibility of type-II IC lasers to operate in continuous wave (cw) mode up to room temperature with high output power. Although significant progress [4-6] has been achieved toward such theoretical projections, the device performance of IC lasers is still far from what they can be at high temperatures, particularly in cw operation. In this presentation, we will report recent progress in mid-IR IC lasers toward high temperature operation with reduced threshold current densities, including device operation in cw mode at TE cooler temperatures (>230K) and above room temperature pulsed operation (up to 350 K) in wavelength range from 3.2 to 3.6 microns. We will discuss feasibility of cw operation at room temperature and above, as well as directions for improving IC laser performance based on experimental data. 1. R. Q. Yang, at *7thInter.Conf.onSuperlattices, MicrostructuresandMicrodevices*, Banff, Canada, Aug. 1994; Superlattices and Microstructures **17**, 77 (1995). 2. J. R. Meyer, I. Vurgaftman, R. Q. Yang, and L. R. Ram-Mohan, Electronics Letters, **32**, 45 (1996). 3. I. Vurgaftman, J. R. Meyer, and L. R. Ram-Mohan, IEEE Photo. Tech. Lett. **9**, 170 (1997). 4. R. Q. Yang, Microelectronics J. **30**, 1043-1056 (1999); and references therein. 5. R. Q. Yang, *etal.*, IEEE J. Quantum Electron. **38**, 559 (2002); and references therein. 6. R. Q. Yang, C. J. Hill, L. E. Christensen, C. R. Webster, SPIE Proc. **5624**, 413 (2005); and references therein.

10:30 AM *EE1.7

Development of high-power room-temperature continuous wave operation of type-I In(Al)GaAsSb/GaSb diode lasers. Jongjin George Kim[1], Haiyan An[1], Ramon U. Martinelli[1], Leon Shterengas[2] and Gregory L. Belenky[2]; [1]Sarnoff Corporation, Princeton, New Jersey; [2]ECE, SUNY at Stony Brook, Stony Brook, New York.

High-power mid-infrared laser sources are required for a wide range of applications, such as bio-photonics, remote-gas monitoring, infrared counter-measures, LIDAR, and secure free-space communications. Room temperature (RT) continuous wave (CW) operation of these lasers will have significant advantages in overall system design and performance over the systems based on lasers with limited, pulsed-mode RT operation or with CW operation that requires cooling. We have fabricated and characterized 2.0- to 2.8-μm wavelength In(Al)GaAsSb/GaSb two-quantum-well diode lasers. The material was grown using molecular-beam epitaxy. All lasers have 2-mm cavity lengths and 100 μm apertures. Continuous wave operation exceeding 1W was recorded at 16 °C from these lasers. Measurements of gain, losses, threshold current, device efficiency and spontaneous emission of the lasers show that it is the hole leakage from QWs into the waveguide, and not Auger recombination that limits CW room temperature output power of long wavelength GaSb-based type-I QW lasers at least up to wavelengths of 2.8 μm. Design approaches to extend the operating wavelength of high power In(Al)GaAsSb/GaSb lasers to more than 3 μm are discussed.

11:00 AM EE1.8

Investigation of Surface Passivation in InAs/GaSb Strained-Layer-Superlattices Using Picosecond Excitation Correlation (PEC) Lifetime Measurement and Variable Area Diode Array (VADA) Analysis. Zhimei Zhu[1], Elena Plis[2], Abdenour Amtout[2], Pallab Bhattacharya[1] and Sanjay Krishna[2]; [1]Electrical Engineering and Computer Science, University of Michigan, Ann Arbor, Michigan; [2]Electrical and Comp Engineering, University of New Mexico, Albuquerque, New Mexico.

InAs/(GaIn)Sb strained layer superlattices (SLS) have recently received significant attention as a promising material system for the fabrication of high performance infrared (IR) focal plane arrays with high quantum efficiency. One of the problems associated with these SLS detectors is the large dark current due to the presence of surface states. These surface states on the etched sidewalls also trap photon-generated carriers, thereby reducing the minority carrier lifetime and decreasing the detectivity. Due to the aforementioned reasons, passivating the surface of InAs/(GaIn)Sb superlattices is an extremely important challenge. In this paper, we report the effect of ammonium-sulfide surface treatments using two complementary techniques, namely, Picosecond Excitation Correlation (PEC) lifetime measurements and Variable Area Diode Array (VADA) dark current measurements. In the PEC measurement, the photoluminescence correlation signal is measured when two identical picosecond laser pulses that are slightly delayed from each other are incident on the sample. The rate at which the PEC signal decays with the delay is a measure of the carrier lifetime. Measurements were undertaken on etched 430μm×430μm mesas, which were passivated in aqueous ammonium sulfide solutions with various strengths for different times. The measurements lead to the following conclusions: (i) Surface states of the as-etched InAs/GaSb superlattices almost reduce the lifetime by a factor of two. (ii) Under all three different passivation conditions, lifetimes are improved by at least 100% due to passivation. (iii) The best passivant found in our experiment is $(NH_4)_2S$ 20%:H_2O=1:4, which increases the lifetime by more than seven times. The surface

leakage current was investigated using VADA analysis with $(NH_4)_2S$ 20%:H_2O=1:4 passivant. Test structures containing mesa diodes with variable areas from 400μm×400μm to 25μm×25μm were fabricated on InAs/GaSb superlattices. The degree that the diode inverse zero-bias resistance-area product ($1/R_0A$) depends on perimeter/area ratio (P/A) is a measure of surface leakage current's influence. The room-temperature (RT) dark current measurements showed that the passivation reduced the diodes' $1/R_0A$ dependence on P/A by over five orders of magnitude, implying suppression of surface leakage currents by passivation treatment. The best-achieved R_0A in passivated diodes was $7.4\times10^4\Omega cm^2$ at RT, indicating state-of-art performance for InAs/GaSb SLS mid-IR photodiode detectors. In the future, silicon nitride thin films will be deposited on passivated diodes to achieve long-term passivation stability.

11:15 AM EE1.9
Improved Morphology and Structural Properties of InAs-GaSb Superlattices Grown on (001) GaAs Substrates by MOCVD for Mid-IR Photodetector Applications. Xue-Bing Zhang[1], Jae-Hyun Ryou[1], Russell Dupuis[1], Shin Mou[2], Shun Lien Chuang[2], Caofeng Xu[2] and Kuang-Chien Hsieh[2]; [1]School of Electrical and Computer Engineering, Gegoia Institute of Technology, Atlanta, Georgia; [2]Micro and Nanotechnology Laboratory, The University of Illinois at Urbana-Champaign, Urbana, Illinois.

InAs layers and InAs/GaSb superlattices (SLs) were grown on GaSb buffer layer on (001) GaAs substrate by metalorganic chemical vapor deposition by using low temperature buffer layer technique. Effects of growth temperature, V/III flow ratio, growth rate, and interface group V passivation on the morphology and the structural properties of SLs have been studied. We show that the formation of InSb at the InAs/GaSb interface is the origin of the nanopipes observed in the grown structures. Through optimizing the growth parameters, the formation of nanopipes is totally suppressed, and the morphology and structural properties of the SLs are significantly improved. Strong absorption in a 5-9 mm wavelength range has been observed in a 30-period SL.

11:30 AM EE1.10
Strain relaxation in compositionally graded GaAsSb/GaAs metamorphic buffer layers. Benny Perez Rodriguez[1] and Joanna Mirecki Millunchick[2]; [1]Applied Physics, University of Michigan, Ann Arbor, Michigan; [2]Materials Science and Engineering, University of Michigan, Ann Arbor, Michigan.

The real-time stress evolution has been investigated during molecular beam epitaxial growth of different grading schemes of $GaAs_{1-x}Sb_x$/GaAs metamorphic buffer layers. The real-time stress evolution was obtained using an in situ multi-beam optical stress sensor (MOSS) measurement, and combined with detailed analysis from x-ray diffraction, transmission electron microscopy, and atomic force microscopy. Constant composition layers of $GaAs_{0.5}Sb_{0.5}$/GaAs initially relax elastically, followed by the rapid nucleation of both 60 degree and pure edge dislocations. There is a very weak temperature dependence of the strain relaxation in these films, contrary to current relaxation models. Step graded buffer layers have less residual stress at the end of growth compared to constant composition layers of the same thickness and ending composition. The strain relaxation could be divided in tree regimes, pseudomorphic, fast relaxation and saturation. Furthermore, most of the strain relaxation takes place in the first layer by the nucleation and glide of a large number of 60 degree dislocations. By the end of the first layer about 81% of the strain is relaxed. As expected, linearly graded layers provide the highest quality material. In this experiment, the Sb incorporation rate was varied from 0 to 0.63 ML/s to obtain a final composition of x=0.5. Several distinct stages of the stress-thickness evolution were observed during growth of linear graded $GaAs_{1-x}Sb_x$ buffer layer. Initially, the stress evolution increased parabolically due to the linear variation in stress. Beyond the 1500 $\AA$ an abrupt decrease in the average stress is observed, indicating the nucleation of misfit dislocation, and the average stress in the film become constant. Preliminary data shows that the compositional linearly grading of GaAsSb, reach higher relaxation with respect to highly mismatched conventional stepwise growths, and enable threading dislocations to glide freely without dislocation-dislocation repulsive interaction. A constant composition $GaAs_{0.5}Sb_{0.5}$ was grown on top of the linearly graded layer and resulted in an increase in the average compressive stress, which may be due to roughening of the surface during growth.

11:45 AM EE1.11
Structural Defect Reduction in InSb Quantum Wells Grown on GaAs (001) Substrates. Tetsuya D. Mishima, M. Edirisooriya, N. Goel and M. B. Santos; Dept. of Physics & Astronomy, University of Oklahoma, Norman, Oklahoma.

Research on InSb quantum wells (QWs) has been motivated by the possibility of mesoscopic magnetoresistors [1] and transport devices that operate in the ballistic regime [2] or exploit spin [3]. Reducing structural defects in the QW is a key to maximizing the performance of such devices. This requirement is demanding, however, because no lattice-matched, semi-insulating III-V semiconductors are available as a substrate material. In spite of its large lattice mismatch (14.6%) with InSb, GaAs has been used as a substrate material for these devices, mainly due to its reasonable price. Previously we reported that micro-twin (MT) density strongly correlates with electron mobility in the QWs [4]. With the aim of decreasing defect density in InSb QWs, we grew four types of buffer layers on GaAs (001) by molecular beam epitaxy. The buffer layers consisted of, in order from the substrate, a ~1 μm nucleation layer, a 1 μm $Al_{0.09}In_{0.91}Sb$ layer, a 50~360nm intermediate layer, and a 2 μm $Al_{0.09}In_{0.91}Sb$ layer. Different nucleation layer material (InSb or AlSb) and intermediate layer structures ($Al_{0.09}In_{0.91}Sb$/InSb strained-layer superlattice (SLS), InSb or $Al_{0.18}In_{0.82}Sb$ interlayer) were used for these buffer layers. $Al_{0.18}In_{0.82}Sb$ and InSb have a lattice mismatch of −0.48% and +0.48%, respectively, with respect to $Al_{0.09}In_{0.91}Sb$. The attached table shows MT and threading dislocation (TD) densities in the InSb QW of the samples measured by plan-view transmission electron microscopy (TEM). The results indicate that the AlSb nucleation layer and the InSb and $Al_{0.18}In_{0.82}Sb$ interlayers are more effective in reducing MT and TD densities than the InSb nucleation layer and the SLS: the lowest MT (1×10^3 /cm) and TD (2×10^8 /cm^2) densities were achieved in sample C which includes the AlSb nucleation layer and InSb interlayer [5]. Sample D, which has an identical buffer layer structure to sample C except the $Al_{0.18}In_{0.82}Sb$ interlayer, also exhibits low defect densities (1×10^3 /cm for MT density and 3×10^8 /cm^2 for TD density). Cross-sectional TEM analysis reveals that TDs are filtered out at the interfaces of both the interlayers, regardless of the differences between them, such as the sign of the lattice mismatch with respect to $Al_{0.09}In_{0.91}Sb$. The $Al_{0.18}In_{0.82}Sb$ interlayer reduces TD density by 75%. We will discuss detailed structural and electronic properties of the samples. [1]S.A. Solin *etal.*, Appl. Phys. Lett. 80 (2002) 4012. [2]N. Goel *etal.*, Physica E 21, 761 (2004). [3]G.A. Khodaparast *etal.*, Phys. Rev. B 70, 155322 (2004). [4]T.D. Mishima *etal.*, J. Cryst. Growth 251 (2003) 551. [5]T.D. Mishima and M.B. Santos, J. Vac. Sci. Technol. B 22, 1472 (2004).

SESSION EE2: Quantum Dot Structures and Devices
Chairs: Robert Biefeld and Chennupati Jagadish
Monday Afternoon, November 28, 2005
Constitution B (Sheraton)

1:30 PM *EE2.1
Electronic properties of InAs/GaAs self-assembled coupled quantum dots: Beyond the effective mass approxiamtion. Jean-Pierre Leburton, Electrical and Computer Engineering and Beckman Institute, University of Illinois, Urbana, Illinois.

In this talk, we discussed the electronic properties of InAs/GaAs self-assembled quantum dots (SAD) with respect to their shapes, sizes and stoichiometric compositions with emphasis on the three-dimensional strain distribution and the piezoelectric potential. Distinctive shape-dependent features in the interband optical transitions of single, vertically stacked and laterally coupled SADs are presented. Particular attention is paid to the quantum Stark effect in single and vertically coupled lens-shaped and truncated-pyramidal SADs. Our analysis based on an 8-band k.p, strain and electric field-dependent Hamiltonian showed good agreement with various experiments.

2:00 PM *EE2.2
Tunneling Injection Quantum-Dot Laser. Shun Lien Chuang[1], Jungho Kim[1], Peter Kondratko[1], Gabriel Walter[1], Nick Holonyak[1], R. D. Heller[2], Xuebing Zhang[2] and Russell D. Dupuis[2]; [1]Electrical and Computer Engineering, University of Illinois at Urbana-Champaign, Urbana, Illinois; [2]School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, Georgia.

Quantum-dot (QD) lasers are expected to be the ultimate coherent semiconductor emitter with lower threshold current density, less temperature sensitivity, and higher gain than the conventional bulk semiconductors. However, carrier injection into the quantum dots has been a challenging issue due to the inhomogeneous QD size distribution and low QD density. A recently proposed quantum-well coupled quantum-dot (QW+QD) active layer improves the carrier collection by the quantum wells and subsequent tunneling injection [2] to the QDs. This "superstructure" of coupling two-dimensional (2D) QWs to a zero-dimensional (0D) QD layer provides a novel quantum system for efficient electron and hole collection and stimulated recombination. Studies of "QW+QD superstructure" lasers show high efficiency, low threshold density, and very small linewidth enhancement factor [3]. In this talk, we investigate a "superstructure"

tunneling injection QD laser both theoretically and experimentally. The superstructure of the laser active region consists of two tensile-strain QWs coupled to a compressive-strain QD layer [3]. Polarization-resolved amplified spontaneous emission (ASE) spectroscopy is used to extract the transverse-electric (TE) and transverse-magnetic (TM) polarized optical gain spectra at very low to high injection currents. At a low current injection, a broad QD ground state TE emission contribution near 680 nm is visible in polarization resolved ASE measurements because of the compressive strain nature of the QDs. A sharper TM emission at a shorter wavelength 643 nm indicates carrier population in the light-hole (LH) subband of the quantum wells. As more carriers are injected, the peak TE emission at 643 nm due to transitions from the QD excited-state coupled QW state in the conduction subband to the heavy-hole (HH) and light-hole (LH) subbands increases. At the same time, the QW TM emission is increased due to the electron recombination to LH subband. At an even higher current above 27 mA, more QD excited states are activated due to strong coupling to the QW state and subsequent lasing occurs in purely TE polarization. We also observed that the optical gain spectra at 293K reveal a turn-on behavior for the TE polarization, and exhibit a symmetrically narrowed gain shape near threshold, while the TM gain spectrum is nearly pinned. The TM gain pinning indicates that the carrier density in the QWs is pinned, while the injected carriers are funneled into the QDs. We will explain the physics of tunneling injection from the QWs into the QDs and how the tunneling injection affects the polarization resolved optical gain spectra as the injection level increases. [1] G. Walter, T. Chung, N. Holonyak Jr., Appl. Phys. Lett. 80, 1126 (2002). [2] S. L. Chuang and N. Holonyak, Jr., Appl. Phys. Lett. 80, 1270 (2002). [3] G. Walter and J. Elkow, N. Holonyak, R. D. Heller, X. B. Zhang and R. D. Dupuis, Appl. Phys. Lett. 84, 666 (2004).

3:30 PM *EE2.3
Scaling Quantum Dot Microcavities: From Quantum Dot VCSELs to Single QD Sources. Dennis Deppe, Jaemin Ahn, Dingyuan Lu, Sabine Freisem, Andreas Muller and C. K. Shih; Electrical Engineering, UT Austin, Austin, Texas.

Quantum dot (QD) nanophotonics combines the scaling of semiconductor photon and electron confinement needed to modify light-matter interaction. In larger cavity lasers, the QD active material can lead to very low transparency current density, temperature insensitive threshold, and greater optical stability. The QD vertical-cavity surface-emitting laser (VCSEL) in some ways bridges the gap between large cavity lasers and microcavities, by providing a microcavity that can be nearly planar and allows scaling of the transverse mode size down to sufficiently small dimensions to observe modified light-matter interaction through the Purcell effect. Planar microcavities were first used to demonstrate the Purcell effect for self-organized QDs, and the QD spontaneous control has since been increased using etched pillar, oxide-apertured, photonic crystal defect, and whispering gallery mode microcavities. More recently, strong coupling has been demonstrated in QD photonic crystal defect and etched pillar microcavities. Lasing in oxide-apertured, photonic crystal defect, and, microdisk microcavities have also been demonstrated using QD ensemble active regions. Although QD nanophotonics could lead to new technologies based on spontaneous quantum light sources and ultra low power, high-speed QD lasers, present semiconductor microcavities have serious drawbacks for practical applications. Perhaps most daunting are the fragilility and poor thermal conductivity that result from thin film photonic crystals, whispering gallery microdisks, or etched pillars. Oxide-confinement suffers poor controllability, making it impractical. Electrical injection in these microcavities is also difficult, if not impossible, especially because of the thin layers. In this talk we will present analysis and experimental data on a new type of all-epitaxial microcavity that uses semiconductor mirrors similar to a VCSEL, and enables scaling of the VCSEL active region into the single QD regime. This microcavity technology uses an intracavity mesa that contains one or more QDs, with epitaxial mirrors grown over this mesa. The epitaxial regrowth is used to form both high Q and low Q microcavities. We have demonstrated high Q cavities in which the Q > 15,000 to obtain lasing even in single layer QD all-epitaxial VCSELs. The spectral emission from lower Q cavities allow clear identification of single QD emission, including exciton, bi-exciton, and high energy excited state transitions from the single QD. The Purcell effect is apparent in these microcavities, both in the blue-shift in the cavity resonance with decreasing mode volume and an increased spontaneous emission efficiency with reducing cavity volume. In this talk we will describe the applications of these microcavities to both low threshold VCSELs and single photon sources, and provide details of the QD growth and fabrication.

4:00 PM EE2.4
Structure, Composition and Optoelectronic Properties of Small Pyramidal Semiconductor Quantum Dots of Ga and In Atoms with As. Liudmila A. Pozhar[1], Alan T. Yeates[2], Frank Szmulowicz[2] and William C. Mitchel[2]; [1]Chemistry, Western Kentucky University, Bowling Green, Kentucky; [2]Materials and Manufacturing Directorate, Air Force Research Lab, Wright-Patterson AFB, Ohio.

Nucleation and growth of small atomic clusters in confinement are dramatically affected by the presence of the environment. This indicates, that the growth conditions can be manipulated with to obtain sub-nanoscale heterostructure (SNHS) units and SNHSs with pre-designed physical, and in particular, optoelectronic, properties. In this study several pyramidal clusters of of Ga and In atoms with As are synthesized and investigated by means of the Hartree-Fock (HF) -based, multi configuration self consistent field method (MCSCF). Some of the clusters have been pre-designed so that the cluster form, stoichiometry and atomic bond lengths reflect the influence of the cluster growth environment. The "vacuum" counterparts of the pre-designed clusters (i.e., similar clusters without any spatial constraints applied to the positions of their atoms) have also been synthesized. These computations prove that the electronic energy level structure (ELS) and direct optical transition energy (OTE) of the clusters can be manipulated up to an order of magnitude by manipulations with the confinement conditions and stoichiometry of the clusters. For all of the studied cases the obtained numerical values of the OTE decrease with an increase in cluster size, in agreement with trends reported in literature for small atomic clusters. The stoichiometry of the synthesized stable clusters is in agreement with that of somewhat larger pyramidal clusters that were recently developed experimentally. While direct comparison of the electronic properties of the virtually synthesized clusters with those of the experimental clusters is not possible due to a substantial difference in the cluster size, scaling of the theoretical results by the cluster size leads to a conclusion that the obtained theoretical results for the OTEs are in agreement with available experimental data. The results of this work indicate that for the studied pyramidal clusters the bond length is a crucial parameter governing the ELSs, while numerical values of the electronic energy levels are determined primarily by the chemical nature of the atoms constituting the clusters. In the case of the OTEs, all parameters and structural details are equally important. Possible mechanisms of optical absorption and lasing in such clusters have also been discussed.

4:15 PM EE2.5
Interdiffused InGaAsP Quantum Dots Lasers on GaAs by Metal Organic Chemical Vapor Deposition.
Ronald Ariwibowo Arif[1], Nam-Heon Kim[2], Luke James Mawst[2] and Nelson Tansu[1]; [1]Center for Optical Technologies, Department of Electrical and Computer Engineering, Lehigh University, Bethlehem, Pennsylvania; [2]Reed Center for Photonics, Department of Electrical and Computer Engineering, University of Wisconsin-Madison, Madison, Wisconsin.

Self-assembled InGaAs quantum dot (QD) lasers on GaAs grown by metal organic chemical vapor deposition (MOCVD) have a natural peak emission wavelength of around 1100-1200 nm due to the MOCVD growth limitation, thus leading to challenges in realizing 980-nm MOCVD-grown InGaAs QD lasers for EDFA pump lasers. In this work, a promising method to blue-shift the emission wavelength of MOCVD-grown InGaAs QD lasers surrounded by GaAsP or InGaP barriers on GaAs to 980-1000 nm are demonstrated by using the post-growth rapid-thermal-annealed (RTA) interdiffusion technique. The RTA interdiffusion of the InGaAs QD with the P-containing barriers (GaAsP or InGaP) results in interdiffused InGaAsP QD, with increased transition energy. During annealing, the interdiffused InGaAsP QD is formed by 1) incorporation of P from the GaAsP or InGaP barriers into the InGaAs QD active region and 2) out-diffusion of In from the InGaAs QD to the barrier region, resulting in significant blue-shift of the peak emission wavelength from 1100-nm regime to 1000-nm regime. Our studies include the photoluminescence (PL) measurements of the RTA-interdiffused InGaAsP QDs, and the laser device characteristics of interdiffused InGaAsP-QDs. The QD lasers studied here include MOCVD-grown InGaAs QD surrounded by P-containing barriers of GaAsP with various P contents. The InGaAs QD lasers with GaAs barriers are also fabricated for comparison purpose. Room- and low-temperature (77K) PL measurements are performed on all samples, with annealing condition ranging from 650-750°C for 0-300 sec. By annealing the InGaAs QD surrounded by $GaAs_{0.8}P_{0.2}$ barriers at 700°C for 300 sec, significant blue-shift in the PL up to 84-nm is observed with reduced PL full-width half max (FWHM) by 11 meV. The room- and low-temperature peak emission wavelengths for the interdiffused InGaAsP QDs with $GaAs_{0.8}P_{0.2}$ barriers (at 700°C for 300 sec) are measured at 1050 nm and 985 nm, respectively, which are considerably shorter than those of as-grown samples (1134 nm and 1075 nm, respectively). The reduction in the FWHM in the annealed QD samples presumably can be attributed to the reduction in the size distribution of the interdiffused QDs, after annealing. Diode laser devices based on 2-stacked InGaAs QD with $GaAs_{0.8}P_{0.2}$ barriers and 3-stacked InGaAs QD with $GaAs_{0.7}P_{0.3}$ barriers are fabricated. For 2-stacked QD as-cleaved laser annealed at

700°C for 200 sec, reasonably low threshold current density of 202 A/cm^2 with emission wavelength at 1075 nm was realized under room temperature operation. The 3-stacked interdiffused QD as-cleaved laser devices demonstrate threshold current density of 250-288 A/cm^2 with emission wavelength at 1040 nm at room temperature operation. Experiments utilizing InGaAs QD surrounded by InGaP barriers grown on GaAs substrate will also be conducted to further investigate the P-species incorporation into the QD gain media, and its impact on laser device characteristics.

4:30 PM *EE2.6
Wavefunction Engineering of Layered Quantum Semiconductor Structures: Recent Progress. L. R. Ram-Mohan, Departments of Physics, Electrical and Computer Engineering, Worcester Polytechnic Institute, Worcester, Massachusetts.

A Lagrangian formulation for the valence bands of bulk zinc blende and wurtzite compound semiconductors provides a direct approach to determining derivative operator ordering at layer interfaces in the multiband $\mathbf{k}\cdots$ description of electronic states, in the envelope function approximation. The current continuity condition is obtained through a gauge-variation on the Lagrangian. The principle of least action together with the discretization of the action integral naturally leads into a finite element approach for the modeling and simulation of the multiband Schrödinger equations. Being a variational method, the wavefunctions and energy eigenvalues can be systematically improved with quadratic convergence. By including the Poisson Lagrangian a self-consistent treatment of the Schrödinger - Poisson band-bending in arbitrarily doped structures is obtained. Numerical examples are presented for the valence band electronic states for quantum wells and superlattices. We have also coupled the finite element method with layer parameter optimizations to design heterostructures for lasers emitting at given wavelengths. It is in this sense that wavefunction engineering goes beyond the notion of bandgap engineering in providing the means for optimizing wavefunction localization in layers, picking layer thicknesses, enhancing optical matrix elements and laser gain. This work was supported by the AFOSR under Grant F49620-03-1-0399 and by DARPA SpinS program under ONR Grant N00014-00-1-0951.

SESSION EE3: Poster Session: Progress in Semiconductor Materials V - Quantum Dots, Growth and Magnetism

Monday Evening, November 28, 2005
8:00 PM
Exhibition Hall D (Hynes)

EE3.1
Effect of strain compensation on multi-stacking of InAs self-assembled quantum dots embedded in GaNAs layers. Ryuji Oshima, Takayuki Hashimoto, Hidemi Shigekawa and Yoshitaka Okada; Institute of Applied Physics, University of Tsukuba, Tsukuba, Ibaraki, Japan.

Recently, high-quality long wavelength quantum dot (QD) devices fabricated on cost-effective GaAs substrates are in a high demand for applications to optical fiber communication systems as well as high-efficiency compound solar cells. One of the challenging problems is to establish a stacking technique of self-assembled QD layers in order to increase the total dot density. If the host material used for burying the QDs is the same as that of substrate, then QDs in a stacked configuration are generally accompanied by an increase of QD size from one layer to the next layer owing to a build up of internal lattice strain with increasing number of stacking. In this work, we study multi-stacked InAs self-assembled QDs embedded in GaNAs strain compensating layers (SCLs) on GaAs (001) substrates grown by atomic-H assisted RF molecular beam epitaxy (H-MBE). Since the lattice constant of GaNAs with diluted nitrogen composition of ~1% is smaller than GaAs, compressive strain induced in InAs QDs layers can be compensated by capping with GaNAs layers which induce the opposite tensile strain. Therefore, one can expect multi-stacking of InAs QDs structures with improved size uniformity and optical properties including the long wavelength emission. First, we performed high-resolution x-ray diffraction (HR-XRD) measurements with symmetric scans around (004) reflection in omega-2theta geometry in order to measure the strain compensation effect of GaNAs SCLs. After optimization of both N composition and thickness of GaNAs SCLs, we were successful in obtaining high quality 20 multi-layer stacking of InAs QD structures without coalescence of QDs or generation of dislocations. Total dot density of 1e12 /cm2 was obtained based on atomic force microscopy measurements.

EE3.2
Enhanced optical interaction of quantum dots in ultra-small mode volume dielectric optical microcavities. Jacob Thomas Robinson, Christina Manolatou, Long Chen and Michal Lipson; Cornell University, Ithaca, New York.

The enhanced interaction between light and matter in optical microcavities is the focus of much research both for potential applications in active photonic devices, as well as experimental studies of these interactions. Many active photonic devices including sensors, switches, and modulators rely on such light-matter interactions as two photon absorption (TPA) and an intensity-dependent refractive index. Increased interaction in gain material such as quantum dots has allowed the development of low-threshold microlasers. Recently, improved light matter interaction between quantum dots and optical microcavities has furthered the study of cavity quantum electrodynamic (cQED) effects such as increased spontaneous emission rate and strong coupling. The effectiveness of these cavities for enhanced optical interaction is often measured by the ratio of the cavity quality factor (Q) to the effective volume of the electric field in the resonant mode (V_{eff}). While there has been much improvement in creating high Q cavities, little progress has been made in developing techniques for decreasing V_{eff} below $(\lambda/2n)^3$ (where λ is the wavelength of light in vacuum, and n is the refractive index of the material). This decrease in V_{eff} is particularly important for applications such as room-temperature quantum dot lasers where once the resonant linewidth of the cavity falls below that of the emitting material (as is the case for quantum dots in high Q cavities) the only means for decreasing the lasing threshold is the reduction of V_{eff}. In this work, we demonstrate a method for decreasing V_{eff} to the order of 10^{-2} $(\lambda/2n)^3$ by introducing a nanoscale slot in the center of the resonant cavity. In semiconductor materials, this can result in a decrease in the lasing threshold and the spontaneous emission lifetime by nearly two orders of magnitude for a single colloidal quantum dot in the slot. This corresponds to nearly a 100-fold increase in the strong coupling g-factor due to the reduction in V_{eff}. We also demonstrate the effect of the small cavity on embedded quantum dots. This development allows for the creation of low-threshold room-temperature quantum dot lasers and further cQED experiments in integrated photonic microcavities.

EE3.3
InAs Growth Mechanisms on Low Index GaAs Orientations in Metalorganic Vapor Phase Epitaxy. Anish A Khandekar[1], G. Suryanarayanan[2], M. Rathi[1], J. Webb[1], S. E. Babcock[3,2] and T. F. Kuech[1,2]; [1]Department of Chemical and Biological Engineering, University of Wisconsin, Madison, Wisconsin; [2]Materials Science Program, University of Wisconsin, Madison, Wisconsin; [3]Deparment of Materials Science and Engineering, University of Wisconsin, Madison, Wisconsin.

InAs is a narrow band gap semiconductor belonging to the 6.1Å family, with applications in high-speed electronic devices and infrared optoelectronic devices. Due to the lack of lattice-matched, high resistivity substrates, InAs films are often deposited on semi-insulating (100) GaAs. The large lattice mismatch between two materials results in a high density of misfit-related defects in InAs films grown directly on GaAs. Growth on non-(100) GaAs planes, as well as the use of the lateral epitaxial overgrowth (LEO) technique have been used to alter the growth morphology and reduce the defect density [Appl. Phys. Lett. 83 (2003) 1977]. The development of InAs surface morphology, strain relaxation and resultant defect microstructure is also reported to be dependent on the orientation of the growth plane [Appl. Phys. Lett. 69 (1996) 776]. The InAs growth mechanisms on alternative low index planes could therefore be important to new device structures. The InAs MOVPE growth was studied on six GaAs substrate orientations: (100), (111)A, (111)B, (110), (211)A and (211)B. The growth was carried out in a horizontal MOVPE reactor, operated at 78 Torr. The effects of growth temperature and the trimethyl indium and arsine gas phase concentrations on InAs growth rate were studied over a broad range of values. InAs growth rate increased by ~50% for (100) planes between 400 and 800°C, whereas growth rate on other planes increased by ~20% over the same temperature range. The slow increase in growth rate with temperature indicated a reactant-transport limited growth mechanism. The highest growth rate was observed on (100) plane, whereas growth was slowest on the (111)A plane. The growth rate increased linearly with TMIn concentration at a constant arsine flux, though the rate of increase depended on the orientation of growth plane. The growth rate stayed almost constant with variation in arsine concentration, indicating a single rate limiting species on all surfaces. The ordering of growth rate with surface orientation agreed with the observed sidewall facets in LEO, which are determined by the slow growth crystal planes. The surface morphology of InAs films as determined by atomic force microscopy, indicated a strong dependence of the surface roughness on growth parameters. The MOVPE growth process was simulated by developing a two-dimensional computational fluid dynamics (CFD) model of the reactor. The model included detailed flow and heat transfer boundary conditions. Radiative heat transfer and parasitic reactions on the reactor walls were included in

the model to accurately predict the measured temperature profiles and growth rate, respectively. The kinetics of multiple gas phase and surface chemical reactions was incorporated in the model to predict the growth rate. Sensitivity analysis of the model is underway to determine the kinetically important pathways and identify the underlying growth mechanism of InAs for different growth planes.

EE3.4
Fabrication of InAs quantum dot memory by selective area MOVPE. Devaraj Nataraj, Noboru Ooike, Junichi Motohisa and Takashi Fukui; Graduate School of Information Science and Technology, Research Center for Integrated Quantum Electronics (RCIQE), Hokkaido University, Sapporo, Japan.

The quantum dot memory devices (QDM) depend on the discrete emission/capture of electrons for its functioning and not on the average behavior of hundreds of thousands of electrons, as is the case in today's Flash memory devices. Large number of reports is available in silicon QDM devices, addressing the fabrication method, room temperature operation, single electron charging effect etc. However, only limited reports are available in InAs QDM devices, and most of them involved several hundreds/thousands of QDs. In the present work, we attempted to fabricate few InAs QDs coupled to GaAs narrow wire channel by selective area metal organic vapor phase epitaxy (SA-MOVPE) and investigated its operation in detail. We utilized a natural width reduction mechanism associated with self-limited mechanism growth of SA-MOVPE to fabricate narrow channel and form few InAs dots on the wire structure. Firstly, wire-like mask openings were formed along [-110] direction on SiO2 masked (001) GaAs semi-insulating substrates using electron-beam lithography and wet chemical etching. In this opening area, AlGaAs/GaAs modulation doped double heterostructures, InAs QDs layer and GaAs capping layer were grown by SA-MOVPE method. Growth of GaAs in a narrow wire like opening on SiO2 masked GaAs (001) substrates is self-limited and therefore the top (001) facet width of our device was narrower than the electron beam lithography defined bottom opening. After the completion of growth, ohmic contact for the source and drain were fomed by the lift-off method. Next, Schottky contact gate to control the 2DEG channel and store/release electrons in QDs was formed using lift-off method. The drain current measurement (Ids-Vg) by sweeping the gate voltage forth and back has resulted in clear hysteresis up to a temperature of 180K. A clockwise hysteresis with a threshold voltage difference value between the reverse and the forward scanning was 165mV at 20K. In scanning electron microscope observation of the wire structure without GaAs capping layer, InAs QDs on the wire structure had a size distribution of 10$\sim$30 nm and with an average density of 25 dots per 0.1 μm$\hat{2}$. In comparison with theoretical estimation, the number of electron in each QD was about six. In real time measurement, the charging and erasing state of our memory device was found to be discriminated for more 5 minutes at 20 K and about 70 seconds at 77 K. These behaviors might be due to the increase in the thermal energy assisted carrier emission from QDs. Consequently, we have successfully fabricated GaAs narrow wire channel coupled InAs quantum dot memory device utilized by SA-MOVPE and obtained memory effect originated from few InAs quantum dots.

EE3.5
Geometrical Effects on the Electronic Dynamics in Coupled Quantum Dots. Hanz Yecid Ramirez[1], Angela Stella Camacho[1] and Lok C. Lew Yan Voon[3]; [1]Physics, Universidad de Los Andes, Bogota, C/marca, Colombia; [2]Physics, Universidad de Los Andes, Bogota, C/marca, Colombia; [3]Physics, Wright State University, Dayton, Ohio.

Minibands of electronic states appear as a consequence of the interaction between neighbor nanostructures. It can be viewed as the result of hybridization of states of the non-interacting components. Such new states exhibit anticrossing behavior when the states of the individual components are in resonance, which is a sign of coupling. We have here studied those states and electronic transitions which are tunable by geometrical parameters in range from radio to terahertz frequencies. The transitions stimulated by external fields, have interesting properties such as coherent emission of radiation, and longer life times of excited states compared with those of quantum wells. These features make coupled quantum dots good options for charge qubits in developing of hardware for quantum computation.

EE3.6
Luminescence of Colloidal Quantum Dots Integrated in Solid Matrices. Jennifer Godwin Pagan[1,2], Edward B. Stokes[2,3], Michael T. Ahrens[1], Kinnari Patel[2], Biemann A. Martin[2,1], Mohamad-Ali Hasan[2,3] and Mark O'Steen[4]; [1]Dot Metrics Technologies, Charlotte, North Carolina; [2]Electrical and Computer Engineering, University of North Carolina at Charlotte, Charlotte, North Carolina; [3]Center for Optoelectronics and Optical Communications, University of North Carolina at Charlotte, Charlotte, North Carolina; [4]Veeco Process Integration Center, Saint Paul, Minnesota.

To date, colloidal quantum dot applications overwhelmingly exist with quantum dots suspended in a liquid solution. Recently the use of colloidal quantum dots has expanded, moving from a predominantly biological arena into electronic device applications, where the quantum dots are no longer used in solution, but rather are integrated into the solid matrix of device heterostructures. In order to facilitate optoelectronic device applications, it is necessary to understand matrix and temperature effects on the optoelectronic properties of quantum dots. In particular, photoluminescence spectra of quantum dots are affected by both temperature and matrix effects. Presented are results of CdSe/ZnS core/shell quantum dots which are integrated into semiconductor as well as insulating matrices. In one set of experiments, quantum dots were deposited onto GaN substrates and overgrown, via low temperature MBE, with GaN. In another, a sputterer was used to deposit SiO2 over the quantum dots. The luminescence of both types of quantum dots is observed at various temperatures.

EE3.7
Spatial Bandgap Tuning in Long Wavelength InAs Quantum Dot-in-Well Laser Structure. Yang Wang[1], Clara Evgenia Dimas[1], Hery Susanto Djie[1], Boon Siew Ooi[1], Gerard Dang[2] and Wayne Chang[2]; [1]Electrical and Computer Engineering, Lehigh University, Bethlehem, Pennsylvania; [2]AMSRD-ARL-SE-EM, U.S. Army Research Laboratory, Adelphi, Maryland.

Self-assembled InAs quantum dots (QDs) grown on InP substrate (lattice mismatch of $\sim$3.2%) has been gaining much attention due to their potential applications in the 1.3-1.6 μm wavelength region for optical telecommunications. However, the precise control of the emission wavelength of this material system at the epitaxial growth level remains to be a challenging issue. Here, we employed the postgrowth impurity-free vacancy diffusion technique to selectively tune the bandgap of the InAs dots-in-AlInGaAs quantum well laser structure grown on (100) InP substrate. The dot-in-well configuration is adopted here to improve the carrier collection rate and to suppress the thermal escape of the carriers. The 1 mm long gain-guided Fabry-Perot lasers fabricated using the as-grown material give a lasing wavelength of $\sim$1.62 μm at room temperature. A blue-shift up to 220nm with a significant decrease in the full width at half maximum (FWHM) has been observed after thermal annealing. The blue-shifts and the FWHM narrowing effect are attributed mainly to the group III atomic compositional interdiffusion, and the reduction in composition and size fluctuation of QDs, respectively. Compared to the typical structure of InAs QDs embedded in the InP matrix [1], the temperature stability of the InAs dot-in-well structure is improved by over 50 °C. Spatial control of the bandgap shifts has been achieved using SiO_2 and Si_3N_4 as annealing masks. A differential wavelength shift as large as 84 nm has been observed from samples capped with Si_3N_4 and SiO_2 followed by a rapid thermal annealing step at 750 °C for 30s. In contrast to most reported results in other material systems, we found that Si_3N_4 capped samples produce a larger energy shift than the SiO_2 capped samples. Similar result has also been observed from the annealed AlInGaAs quantum-well samples ($\lambda_g \sim 1.3$ μm) that have similar wafer structure but without the presence of the InAs QDs in the active region. The detailed mechanism of this intermixing process is still under investigation. However, from theoretical calculations, we postulate that the intermixing of this material system might be governed by different interdiffusion rates of group III atoms in the Al-quaternary. This high spatial bandgap modification process will be advantageous for postgrowth on-wafer emission wavelength tuning, as well as for the fabrication of photonic integrated circuits using this material system. [1] C. K. Chia, S. J. Chua, S. Tripathy, and J. R. Dong, Appl. Phys. Lett. 86, 051905 (2005).

EE3.8
Material Synthesis and Infrared Optical Properties of Transition Metal Doped Binary and Ternary II-VI Semiconductors. EiEi Nyein[1], Uwe Hommerich[1], Ivy K. Jones[1], Sudhir Trivedi[2] and Althea G. Bluiett[3]; [1]Hampton University, Hampton, Virginia; [2]Brimrose Corporation, Baltimore, Maryland; [3]Elizabeth City State University, Elizabeth City, North Carolina.

We report on the material preparation and optical characterization of transition metal (TM) doped binary and ternary II-VI chalcogenides for applications in mid-infrared (MIR) light source development. Cr^{2+} doped II-VI semiconductors (ZnSe, ZnS, CdSe, CdMnTe) have received world-wide attention for MIR solid-state laser development in the 2-3 μm region. Lasing at $\sim$4 μm has been demonstrated from Fe doped ZnSe, but only at low-temperatures. TM doped II-VI thin films are also currently being studied for the development of broadly tunable mid-infrared lasers pumped through electrical carrier-injection or impact excitation. In this paper, we present results of the material synthesis and IR spectroscopy of several TM doped ternary cadmium chalcogenides including CdMnTe, CdZnTe, CdMgTe, CdSrTe, CdBaTe, and CdTeSe. Following the synthesis, purification, and

Bridgman crystal growth of the investigated host materials, TM doping was performed through a thermal diffusion process. The TM doping experiments focused mainly on Cr^{2+}, but some initial results were also obtained for doping and co-doping of II-VI's with $Co^{2+}$and Fe^{2+} ions. For comparison, TM doped binary II-VI's (ZnSe, ZnTe, and CdTe) were also prepared. The Cr^{2+}doped II-VI materials were characterized by broad IR absorption bands centered ~1800-1900 nm. All samples exhibited a broad MIR emission at room temperature extending from ~2000-3500 nm. The emission lifetimes varied between 1-5 μs, depending on the Cr concentration and host composition. Compared to Cr doped binary II-VI's, Cr doped ternary materials exhibited a larger emission bandwidth indicating inhomogeneous broadening due to multiple Cr^{2+}centers. More details on the IR absorption and emission properties (spectral, dynamics) of TM doped binary and ternary II-VI' s will be presented at the conference.

EE3.9

InGaAs/InGaAsP Quantum-Well Engineering for Multiple Regrowth MOVPE Process. H.-J. Lohe[1], E. Gini[2], R. Scollo[1], F. Robin[1] and H. Jaeckel[1]; [1]Electronics Laboratory, ETH Zurich, Zurich, Switzerland; [2]FIRST Center for Micro and Nanoscience, ETH Zurich, Zurich, Switzerland.

Mode locked laser diodes (MLLDs) are key devices for all-optical Tbit/s communication networks. We have proposed the use of a fast recovering absorber based on an uni-travelling-carrier structure (UTC) to achieve pulsewidths below 1 ps. This requires the integration of three separate layer stacks for: the absorber, unstrained InGaAs/InGaAsP multiple quantum well (MQW) gain and passive waveguide. We use a butt-coupling process that involves up to 5 MOVPE regrowths in order to optimize the internal reflections at the interfaces. Because the MQW-structure is the layer stack most sensitive to planarization issues, it is grown first onto the blank wafer. Due to the repeated thermal cycling of the QW up to 630C during the subsequent growth steps we have to account for the blue shift based on QW intermixing. The MQWs emission wavelength has to be matched with the UTC absorption spectrum with an accuracy of better than 5 nm. Fabry-Perot laser diodes processed on every MLLD-Wafer were used to probe the gain characteristics, as they match the relevant output wavelength of our MLLDs and undergo exact the same growth conditions not provided by simple thermal cycling of as-grown MQWs. Therefore the laser spectral peak was compared with the PL-peak before regrowth. The five investigated wafers showed a blue shift between 0 and 45 nm depending on cumulative heating time over all regrowth steps (0-3h) and the initial photoluminescence(PL)-peak wavelength. The blue shift is explained in terms of structural change during regrowth at the interface between the InGaAs wells and InGaAsP barriers due to group V diffusion. We therefore compute an effective width for the QWs as grown and after the regrowth steps by solving the one-dimensional Schroedinger equation to get the conduction- and valence band energy states and transition wavelength for various QW widths. Assuming that both the PL-peak and the spectral gain peak correspond to the transition between ground states in the conduction and valence bands, we can assign a corresponding quantum well width to all PL and spectral gain peaks. The total wavelength shift is highly dependent on the initial PL-peak, as the interband transition energy is not linearly dependent on the quantum well width. Initial PL peaks of 1555/1574nm resulted in wavelength shifts of -45/-35nm respectively for a cumulative heating time of 3h. This corresponds to an effective quantum-well width shrinkage of 25 A for both samples. All five investigated wafers show a linear relationship between the effective quantum well width shrinkage and the cumulative heating time of 8.3 A/h at a growth temperature of 630C. Therefore knowing the cumulated regrowth time we can design the initial quantum-well thickness that yields the targeted emitting wavelength. In conclusion, we have developed an easy to use method to account for the quantum well intermixing in regrowth processes.

EE3.10

Maximum Entropy Mobility Spectrum Analysis of HgCdTe Heterostructures. Gwladys Perrais, Jerome Meilhan, Olivier Gravrand, Jacques Baylet, Philippe Ballet and Johan Rothman; LETI/DOPT, CEA, Grenoble, France.

We report on Mobility Spectrum Analysis, of HgCdTe using a new Maximum Entropy, ME, algorithm. MSA was proposed by Beck to estimate carrier properties in mixed conductivity systems, by adjusting a semi-continuous mobility spectrum to the applied magnetic field dependence of the conductivity tensor. MSA is well adapted to determine the carrier properties in narrow gap semi-conductors, but also in hetero structures used in the third generation of FPAs, for example multicolour detectors. Compared to other approaches, such as multi carrier fits, MSA presents the advantage that it does not need any hypothesis on the number of carriers present in the sample. Maximum Entropy Mobility Spectrum Analysis, MEMSA has been shown to be a viable alternative to the more commonly used Quantitative Mobility Spectrum Analysis, QMSA. The use of maximum entropy algorithms for MSA is more philosophically satisfying than the QMSA, as the MEMSA does only make use of basic principles in information theory and is well adapted to estimate a large set of parameters (the mobility spectrum), from a reduced set of experimental parameters (the Hall data). The QMSA on the other hand, is based on least square minimisation and is working thanks to a good initial spectrum, the Beck spectrum, and a clever algorithm. Our MEMSA algorithm uses Lagrange multipliers to maximise the entropy and neglects random experimental noise, as the algorithm used by Kiatgamolchai et al.. In difference to previous reports, we separate the constraints on the two components of the conductivity tensor. This approach should be advantageous in mixed conductivity systems with very small Hall coefficients. Mobility Spectrum Analysis has been performed on synthetic data and experimental data using both the MEMSA and the Lakeshore commercial QMSA software. The capacity of each algorithm has been tested on synthetic data. For a synthetic data set with five contributions to the conductivity, MEMSA gives a more accurate estimation of the mains contribution to the conductivity and shows a higher sensitivity to estimate small contributions to the conductivity in mixed conductivity systems. Mobility spectrum estimations on experimental data will be reported for single epilayers of HgCdTe and for more complex heterostructures used in multicolour detectors. Concerning the single epilayers, we report the systematic appearance of artefacts for some type of samples, often observed as mirror peaks of main contribution in the mobility spectrum, which will be discussed in terms of sample geometry and in homogeneity. For the multilayer samples, we will focus on the estimation of the transport properties in deep lying layers in the heterostructures.

EE3.11

Quantum-well Intermixing using Ge-doped Sol-gel Derived Silica Encapsulant Layer. Hery Susanto Djie[1], Boon-Siew Ooi[1], Charles K. F. Ho[2], Ting Mei[2], Kantisara Pita[2] and Nam-Quoc Ngo[2]; [1]Center for Optical Technology, Department of Electrical and Computer Engineering, Lehigh University, Bethlehem, Pennsylvania; [2]School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore, Singapore.

Post-growth bandgap modification through quantum-well intermixing (QWI) has generated considerable interest due to its simplicity and effectiveness for photonics integrated circuits through the use dielectric encapsulant impurity-free technique. It is widely known that the sol-gel method allows the synthesis of stoichiometric-dielectric materials, in which the matrix material can be doped with a wide range of elements and concentration homogeneously in a simple and inexpensive way [1]. Here, we investigate the role of intermixing using the sol-gel derived silica encapsulant layer doped with Germanium to trim the bandgap energy of quantum-well at postgrowth level. The intermixing is reproducibly enhanced in InGaAs/InGaAsP quantum well laser structure using the Ge-doped sol-gel derived silica encapsulant layer after the subsequent annealing. A bandgap shift of ~64 nm has been observed from 16% Ge-doped silica capped sample at an annealing temperature of 630°C with effective intermixing suppression using the e-beam evaporated SiO_2 layer. Using our model [2], a nearly identical activation energy of 1.7±0.5 eV intuitively implies that the dissimilarity in interdiffusion behavior between 0% and 16% Ge-doped silica capped sample is only attributed to the difference in the number of beneficial vacancies that involve in the intermixing process. To confirm the postulation, we further analyze the intermixing enhancement using the multiple-width GaAs/AlGaAs quantum-well probe structure allowing the intermixing process identification related to the injection of Ga vacancies. We found that the enhanced bandgap blue-shift as the increase in Ge content in the sol-gel derived silica cap is related to Ga outdiffusion to encasulant layer, and V_{Ga} in-diffuses to the quantum-well area and promote the local intermixing. The above compositional dependence can be explained by Ge incorporation in the sol-gel cap reduces the mismatch of thermal expansion coefficients between the quantum-well structure and film, efficiently retaining preferential vacancies, and therefore enhancing the interdiffusion rate between wells and barriers. The intermixed material retains a good surface morphology and preserves the optical quality as evidenced by the absence of any appreciable photoluminescence linewidth broadening. By choosing appropriate annealing temperature and Ge incorporation, the Ge-doped sol-gel enhanced intermixing has the potential to offer unique impurity-free interdiffusion process capabilities such as low-temperature annealing activation with spatial bandgap selectivity in a simple and cost-effective way. [1] C.K.F. Ho, H.S. Djie, K. Pita, Q.N. Ngo, & C.H. Kam, Electrochem. Solid-State Lett. 7, 96 (2004). [2] H.S. Djie, S.L. Ng, O. Gunawan, P. Dowd, V. Aimez, J. Beauvais, & J. Beerens, IEE Proceedings-Optoelectronics, 149(4), 2002, 138-144.

EE3.12

Purification, material synthesis, and infrared emission from Nd doped $PbBr_2$ and PbI_2. Uwe Hommerich[1], EiEi Nyein[1], Amethyst Phillips[1], Sudhir B. Trivedi[2], Althea G. Bluiett[3] and John

M. Zavada[4]; [1]Hampton University, Hampton, Virginia; [2]Brimrose Corporation of America, Baltimore, Virginia; [3]Elizabeth City State University, Elizabeth City, North Carolina; [4]US Army Research Office, Durham, North Carolina.

Lead halides (PbI_2 and $PbBr_2$) have emerged as promising materials for room-temperature nuclear radiation detectors. PbI_2 and $PbBr_2$ are considered wide-gap semiconductors with gap energies of ~2.2 eV and -~2.5 eV, respectively. The high atomic number of the cation and the wide bandgap make these materials attractive candidate for scintillator or semiconductor detectors. We are currently exploring the purification and rare earth doping of $PbBr_2$ and PbI_2 for possible applications as infrared light emitters under optical and electrical pumping. Commercially available 5N purity $PbBr_2$ and PbI_2 were further purified through repeated solidification and horizontal zone refinement. 1 wt% of $NdBr_3$ was mixed to purified lead halides before Bridgman growth. Following optical pumping at 808 nm near-infrared emission bands from Nd^{3+} ions were observed at ~900 nm, 978 nm, 1080 nm, 1200 nm, 1380 nm, and ~1580 nm. The rich near infrared emission spectrum from Nd doped lead halides can be explained by the small maximum phonon energies of the host materials (< 200 cm^{-1}), which result in reduced non-radiative decay rates between closely spaced excited states of Nd^{3+}. In contrast to Nd: YAG, Nd doped lead halides exhibit efficient emission from several excited states including the $^4F_{5/2}$ and $^4F_{3/2}$ levels. Moreover, efficient mid-IR emission at ~5 μm was also observed from Nd: $PbBr_2$. Initial experiments were carried out to growth thin-films of Nd: PbI_2 through isothermal vapor phase epitaxy. The thin-film sample of Nd: PbI_2 exhibited near infrared emission under optical pumping, but at slightly shifted wavelengths. More details on the material preparation and infrared emission properties of Nd doped $PbBr_2$ and PbI_2 will be presented at the conference.

EE3.13

The Development of Morphology and Onset of Crystal Tilt during Island Growth of InAs Films Deposited on Unmodified and Mask-Patterned (100) GaAs Substrates.

Ganesan Suryanarayanan[1], Anish A. Khandekar[2], Thomas F. Kuech[2,1] and Susan E. Babcock[3,1]; [1]Materials Science Program, University of Wisconsin - Madison, Madison, Wisconsin; [2]Department of Chemical Engineering, University of Wisconsin - Madison, Madison, Wisconsin; [3]Department of Materials Science and Engineering, University of Wisconsin - Madison, Madison, Wisconsin.

The use of semi-insulating GaAs as a substrate of choice for novel devices containing the low band gap semiconductors InAs, GaSb and AlSb drives interest in developing new substrates and growth processes that circumvent defects induced by the 7% mismatch between the film and substrate. InAs films grown on unmodified GaAs substrates under conditions that favor low nucleation and/or high growth rates tend to have high threading dislocation densities and also show a systematic crystal tilt of the InAs grains of ~4° in one of six preferred directions relative to the GaAs substrate. The defect microstructure and crystal tilt for InAs grown under the same reactor conditions that promote profuse crystal tilt are altered substantially when a lateral epitaxial overgrowth (LEO) method on mask-patterned stripe-shaped windows is used to grow the film, provided that the windows are < 1μm in width. Not only do a substantial reduction in dislocation density and a complete change in dislocation arrangements result, but also orientational purity is achieved in which all of the InAs is crystallographically aligned with the GaAs substrate. The purposes of this study were to explore the origins of the tilt, to uncover the chemical, physical and topological conditions that favor tilt amelioration and to understand the mechanism(s) by which tilt occurs and can be inhibited. To do so, the island morphology and localized crystal orientation within isolated islands of various sizes in pre-coalesced InAs films were studied. The island morphology was determined from AFM, SEM images. Backscattered-electron Kikuchi diffraction pattern (BEKP) analysis and BEKP-based orientation imaging microscopy (OIM) were used to detect and measure local tilt within individual islands. The combined analyses for islands grown on unmodified GaAs wafers showed that the islands are equi-axed and aligned with the substrate during the initial stages of growth. The smallest islands around 300-500nm are pyramidal with (111) facets whereas the micron-size islands show combination of (110) and (111) facets. As the islands approach 1μm in lateral extent, they extend in the [0-11] direction to form an elongated diamond foot print, develop rough, stepped surfaces, and whole blocks of material within each island tilt locally in one of six directions in a pattern that is repeated from island to island. These six orientations are retained in the film as the islands coalesce and as the film thickens. Parallel work has shown that the tilting is circumvented by forcing island coalesce to occur before reaching ~1μm in lateral extent, either through chemical control of the reaction kinetics or physical control of the arrangement of islands thought mask patterning. Window widths of < 1μm cause copious nucleation at the mask-edges and force coalescence at small island size. BEKP demonstrates that these islands are aligned with one another indicating that substrate topography can be used to manipulate growth.

EE3.14

Epitaxial growth and characterization of BP(100) on Si(100) substrate.

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Boronmonophosphide(BP) is one of the III-V semiconductors having the zinc-blende structure. Recently, the technologies of c-GaN and GaN growth on Si substrate have attracted much attention of many researchers. BP(100) is one of the suitable materials for buffer layer between the c-GaN(100) and Si(100) substrate. BP and c-GaN have the same crystal structure and the lattice mismatch is about 0.7%. This value is relatively lower compared to GaAs(about 20%) and 3C-SiC(about 3.3%) which is mainly used for substrate to study c-GaN growth. The growth of BP layer was carried out by MOCVD on Si(100) substrate of 2 inch in diameter. As Si substrates the both p-(B-doped) and n-(P-doped)type with 0.01-0.1 ohm-cm were used. TEB and TBP were used for the gas sources of Boron and Phosphorus, respectively in H_2 gas carrier. Before beginning the high temperature layer growth, the low temperature layer was deposited around 450°C. The growth rate was over 1μm/hour without any troubles such as the bending or cracking. In addition, the thickness of epitaxial layer was uniform. The deviation was within 5% at 1.24μm thickness. The BP epitaxial wafers obtained under these conditions were evaluated in terms of SEM, TEM, XRD, AFM and Hall effect measurement. The x-ray diffraction showed that two strong peaks of BP(200) and BP(400). This result suggests that the BP epitaxial layer grown was inherited the crystal orientation from Si(100) substrate. Under the above growth conditions, there were no distinct peaks except substrate diffractions. In the case of B-rich conditions, the others type of Boronphosphide were appeared. It has been found that $B_{13}P_2$ having the rhombohedral crystal structure is mixed in the layer. Near the interface between BP layer and Si substrate, TEM images gave the some defects like dislocations. The Hall effect measurement indicates that the conduction type of every BP films grown on the both n-Si and p-Si substrates were n-type without impurity doping, and the mobility and carrier concentrations were typically 350cm^2/Vs and $10^{20}cm^{-3}$(on n-Si) and 65cm^2/Vs and $10^{19}cm^{-3}$(on p-Si), respectively.

EE3.15

On the nucleation of GaP/GaAs and the effect of buried stress fields.

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In this work we study the growth of GaP/GaAs by chemical beam epitaxy (CBE) and the role of a buried InP dots array on GaP nucleation in order to obtain three-dimensional structures. Our samples were grown by CBE with in-situ monitoring by Reflection High Energy Electron Diffraction (RHEED). GaP films 4 to 10 monolayers (ML)-thick were deposited. The growth temperatures were 540 and 550øC. The topography of the samples was investigated with in-air Atomic Force Microscopy (AFM). The characteristics of GaP films grown on unstressed GaAs were evaluated by means of surface roughness and size distribution for GaP nucleation islands, as well as from the RHEED patterns formed during deposition and cool down. Even though GaP/GaAs growth is assumed to occur in theWolmer-Weber mode, a two-dimensional (2D) RHEED pattern was observed for all samples grown. For the 4ML-thick samples, we noticed a dependence of the RHEED 2-3D transition on the As/P switch times. This is most likely due to As contamination of the first GaP MLs, thus increasing the critical thickness for 3D nucleation. The 4ML sample with larger As/P switch time shows a chevron-like RHEED pattern usually associated to dot formation but no such dots can be observed in the AFM images. A large density of small dots (diameters ~ 22nm and heights ~1.5-2nm), however, is observed for the 6ML sample. On the other hand, for thicker GaP films there is a ten-fold increase in roughness and the formation of large depressions where growth seems to be inhibited. This morphology suggests that growth is taking place preferentially at the top of the 3D islands from this point on. This behavior may result from kinetically-driven material redistribution on the surface due to strain relaxation in the film. The nucleation of GaP on stressed GaAs was accomplished by using buried arrays of InP dots grown on InGaP buffer layers with periodic compositional modulation. The GaP nucleation was studied with AFM and High Resolution Transmission Electron Microscopy (TEM). AFM images for these GaP samples show larger dots, with lateral size and spatial ordering compatible with the burried InP array. For GaP films deposited on top of compositionally-modulated InGaP layers, however, GaP dots with a wider size distribution, and

lower spatial ordering on the surface, was observed. These results show that GaP nucleation is indeed affected by the stress field of the InP dots. zelcovit@ifi.unicamp.br

EE3.16
Effects of Temperature and Strain on Dislocation Glide on {110} Planes in Zinc-Blend Materials (InP and InGaAs) Grown on a (001) Surface. Nate Quitoriano and Eugene A. Fitzgerald; MIT, Cambridge, Massachusetts.

Using plastically relaxed metamorphic buffers, InP devices could be grown on larger GaAs wafers and use the GaAs manufacturing infrastructure to reduce costs and open the use of InP devices to new, lower-cost applications. We have studied in detail a variety of materials systems to achieve high-quality InP on GaAs. As a result of our study, we can grade up to $In_{0.34}Ga_{0.66}As$ retaining low threading dislocation densities of $1.5x10^6/cm^2$. However, as we approach $In_{0.53}Ga_{0.47}As$ (InGaAs lattice matched to InP) composition modulation interferes with dislocation flow, resulting in high dislocation densities. To circumvent composition modulation, we attempted using partially-relaxed InP on $In_{0.34}Ga_{0.66}As$ to achieve low threading dislocation density InP on GaAs. In the process we have discovered that a significant amount of relaxation at the InP/ $In_{0.34}Ga_{0.66}As$ interface is relieved by the activation of an alternative slip system. The primary slip system in diamond-cubic and zinc-blend materials is a/2<110>{111}. (The notation indicates the burgers vector whose length and direction is a/2 <110> while gliding on a {111} plane). Compressively strained InP deposited on $In_{0.98}Ga_{0.02}P$ [misfit of 0.16% compositionally graded from (001) GaAs] relaxes via this slip system with <110> type line directions. We have found, however, that depositing InP (or $In_{0.53}Ga_{0.47}As$) on relaxed $In_{0.34}Ga_{0.66}As$ activates a secondary slip system, a/2<110>{110}, with <100> line directions. There is a misfit of 1.6% between InP (or $In_{0.53}Ga_{0.47}As$) and $In_{0.34}Ga_{0.66}As$. Interestingly, the amount of relaxation accomplished via the secondary slip system is a function of temperature where lower temperatures favor the secondary, a/2<110>{110}, slip system. At all temperatures in all samples, however, cross slip between the primary and secondary systems is prominent which indicates that the <110> burgers vectors are not dissociated into partial dislocations which is common in lower mismatched systems. Other authors have reported the existence of this slip system on the (001) interface in the InGaAs [1], SiGe [2], $InAs_{0.48}P_{0.52}$ [3] and InAs [4] materials systems. However, primary relaxation via this slip system using MOCVD has not been reported and no systematic study on strain or temperature has been done. We report the effect of temperature and strain on the relaxation via the a/2<110>{110} slip system and the effect on threading dislocation density when using this system to relax lattice mismatched materials.
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EE3.17
Growth of GaAs on (100) Ge and Vicinal Ge Surface Using Migration Enhanced Epitaxy. Hendrix Tanoto[1], S. F. Yoon[1], W. K. Loke[1], E. A. Fitzgerald[2], C. Dohrman[2], B. Narayanan[3] and C. H. Tung[3]; [1]Nanyang Technological University, Singapore, Singapore; [2]Materials Science and Engineering, Massachusetts Institute of Technology, Boston, Massachusetts; [3]Institute of Microelectronics, Singapore, Singapore.

In this paper, we present GaAs/Ge heteroepitaxy grown by RIBER32 solid-source molecular beam epitaxy (SSMBE) with the initial GaAs nucleation by migration-enhanced epitaxy (MEE) technique. We look at the influence of substrate temperature during the MEE and the influence of Ge surface orientation to the quality of the GaAs layer. Three samples were grown for this study; the first two samples, sample A and B, have surface orientation of (100) 6° offcut towards (111) plane. This surface orientation was chosen as to achieve double-atomic steps surface that is crucial to suppress anti-phase domain (APD) formation. These samples were then subjected to different temperature during the MEE process, 450°C for sample A and 250°C for sample B. The third sample, sample C, has the same MEE substrate temperature as sample A, which is 450°C but with nominal (100) surface orientation. The growth conditions and the structure of the layers after the MEE process were kept constant across the three samples. We examine the structures and the optical quality of the samples by cross-sectional Transmission Electron Microscope (XTEM) and 5K photoluminescence (PL). Analyzing the XTEM images of sample A and B, it is found that the APD still appear in sample A while it is suppressed totally in sample B. It is also observed from the sample A XTEM images that two APDs propagating at 45° and 135° angle, as measured from the GaAs/Ge interface, could meet with each other at certain layer thickness leading to self-annihilation. However, some of the self-annihilations took place only after the APDs propagated hundreds of nanometers in the GaAs layer, producing large undulation in the layer. As for sample B, we believe that the APD suppression is mainly due to the much lower nucleation temperature. At such low temperature, As dimers are adsorbed onto the substrate surface more readily with negligible re-evaporation. This ensures complete As coverage on the double-atomic steps Ge surface and minimize As vacancies that may act as defect initiation centers. Furthermore, the low substrate temperature shortens the migration distance of Ga adatoms, minimizing their adsorption into the kinks and step edges, resulting in two-dimensional growth mode instead of step-flow growth mode. Meanwhile, XTEM images of sample C show APDs that propagate almost perpendicularly to the GaAs/Ge interface, making it unlikely for the self-annihilation mechanism to take event. It is understood that the direction of propagation of the APD relies on the atomic steps reconstruction on the Ge starting surface. In the case of single atomic-step surface, the APDs propagate almost perpendicularly to the interface. Finally, the 5K PL spectra of the embedded InGaAs single quantum-well in all the samples clearly demonstrate that the best optical quality comes from sample B; which we believe mainly due to the total suppression of APD, leading to much improved layer quality.

EE3.18
Metal Stack Study and Optimization for n- and p-type Contact for GaAs-Based Laser Applications. Pedro J Barrios, Margaret Buchanan, Phillip Chow-Chong, Simona Moisa and Michael Graham; Institute for Microstructural Sciences, National Research Council of Canada, Ottawa, Ontario, Canada.

In an effort to reduce unwanted laser heating due to contact series resistance of medium to high power semiconductor lasers, we have investigated six dissimilar metal stacks on n-type and p-type GaAs by e-beam evaporation and rapid thermal annealing. These stacks ranged from common variations of NiGeAu to more exotic ones like PdGeTiPtAu with series contact resistivities in the 1e-4 to 1e-7 $ohms.cm^2$, for the n-type contact and metals like TiPtAu to AuZnAu for p-type GaAs with series contact resistivities in the 1e-4 to high e-6 $ohms.cm^2$. TLM measurement results as a function of annealing temperature from 350 to 500 °C in forming gas for annealing times between 15 to 60 sec, morphological micrographs, as well as comparative Auger depth profiles of the best stacks will be presented.

EE3.19
Microstructure Analysis and Wafer Bonding of Low-temperature Grown GaAs. Chaofeng Xu[1], Kuang-Chien Hsieh[1] and Kuo-Lih Chang[2]; [1]Department of Electrical and Computer Engineering, and Micro and nanotechnology Laboratory, Uinversity of Illinois at Urbana-Champaign, Urbana, Illinois; [2]Applied Materials Inc., Sunnyvale, California.

We have bonded two low temperature (LT) grown single crystal GaAs and explored As precipitation and its role in bridging two crystals during direct wafer bonding. In our work, a 500 Å LT GaAs layer was deposited at 200 ^oC on the 1500Å n-type GaAs buffer grown at normal growth temperature. Transmission electron micrographs show no discernible differences between LT GaAs layer and the underlying GaAs buffer. Arsenic precipitates about 20 Å in size are clearly visible after the LT GaAs have been annealed at 600 ^oC for 10 minutes in vacuum with As overpressure. The uniformly distributed precipitates extend 1000 Å beyond the LT GaAs layer into the buffer, The results of precipitation and its distribution are consistent with those reported in the literature. Direct wafer bonding of the LT GaAs is performed at 400 ^oC for one hour under force. TEM shows an uneven bonding layer exists between the bonding wafers. The bonding layer varies in thickness from 10 Å to 40 Å, and is amorphous possibly consisting of $GaAsO_4$ or other oxide. Symmetrically next to the amorphous bonding layer are two distinctive 500 Å layers each densely packed with tiny As precipitates. Apparently the As precipitation is completely confined within the original LT GaAs layer when annealed at 400 ^oC. The bonded LT GaAs sample is then annealed at 600 ^oC for 10 minutes without any applied mechanical stress. As precipitates again migrate into the GaAs buffer as those in annealed but unbonded wafers. However, the distribution of As precipitates is no longer uniform but exhibits a U-shape distribution, i.e. As precipitates are denser and larger near the surface and toward the substrate. In addition to the segregation of As precipitates, segmentation of the bonding layer also takes place. This study of As precipitation in the bonding of LT GaAs provides an excellent means to understanding the point defect diffusion and its underlying correlation to the As precipitation as well as wafer bonding mechanism.

EE3.20
Cathodoluminescence study of orientation patterned GaAs films for non linear optics. Manuel Avella[1], Juan Jimenez[1], David Bliss[2], C. Lynch[2] and D. Weyburne[2]; [1]Fisica Materia Condensada, Universidad de Valladolid, Valladolid, Spain; [2]Air Force Research

Laboratory, Hanscom AFB, Hanscom, Massachusetts.

Zincblende semiconductor materials, particularly GaAs and ZnSe, are very promising for optical frequency conversion by quasi phase-matching techniques. GaAs has a large second order non-linear optical coefficient, high transparency in the 2-12 micron range, a high damage threshold, and it offers the advantage of integration with semiconductor lasers. Templates for antiphase domain gratings on GaAs substrates were produced by photolithography and growth of GaAs/Ge/GaAs by molecular beam epitaxy (MBE). Subsequently, thick layers of orientation patterned GaAs (OP-GaAs) were grown by low-pressure hydride vapor phase epitaxy (LP-HVPE). HVPE allows thick growth (up to 1mm) of GaAs antiphase domain arrays. The challenge is to achieve regular vertical domains with well-defined sidewalls. Both, crystal defects and strain fields must be controlled in order to optimize the OP-GaAs for use in non-linear optical devices. We present a complete cathodoluminescence (CL) analysis of the OP-GaAs grown by LP-HVPE. The structure of the antiphase domain grating is revealed by panchromatic CL images of cleaved surfaces. The main crystal defects as well as their origins are revealed. A spectral analysis revealed strain fields around the domain walls. We also describe the main features of dislocations formed during the layer growth.

EE3.21
Crystallization of Boron-rich Crystals from High Temperature Copper Solutions. Christopher Maier[1] and Linda Jones[2]; [1]School of Engineering, Alfred University, Alfred, New York; [2]Picker Engineering Program, Smith College, Northampton, Massachusetts.

Boron-rich solids form a unique class of materials that are essentially comprised of rigidly-bound three-dimensional networks of icosahedral (B_{12}) clusters. The ability of these networks to accommodate additional atoms in the form of 2-3 atom inter-icosahedral linear segments, other icosahedral fragments and condensates, directly substituted species within B_{12} icosahedra, as well as interstitially dissolved solute atoms manifests itself in the stabilization of a variety of ordered structures. The electronic properties of these materials vary from conductive semiconductors to wide band gap insulators. As the boron-copper binary system is of the simple eutectic type, substantial amounts of boron are soluble in liquid copper at high temperature, and no intermediate boride phases exist, the use of copper as a high temperature flux for the growth of boron-rich crystals is particularly advantageous for the growth of boron-rich single crystals. The results of a crystal growth study are presented wherein rhombohedral boron-rich crystals are prepared from high temperature copper solutions saturated with boron and carbon. The presence of carbon results in the simultaneous precipitation of both the boron carbide (B_xC) and copper-saturated β-boron (CuB_{23}) phases. The composition, structure, and morphologies of the resultant crystals are analyzed as a function of the B:C ratio in solution. Conditions for crystal growth and approximate solubility limits as a function of the B:C ratio in solution will also be discussed.

EE3.22
Optoelectronic properties of RF sputtered CuCl thin films. Gomathi Natarajan, Anirban Mitra, Lisa O'Reilly, Stephen Daniels, David Cameron, Patrick McNally, Olabanji Lucas and Louise Bradley; Electronic Engineering, Dublin City University, Dublin, Ireland.

Copper (I) chloride is a potential candidate for UV optoelectronics due to the fact that it is closely lattice matched to Si which makes it readily integrable with silicon device technology. The structural and optoelectronic properties of CuCl thin films deposited on glass and Si by RF magnetron sputtering are investigated in detail. The crystallinity is studied using X-ray diffraction which confirms the growth of CuCl thin films with cubic zinc blende structure predominantly orientated in the (111) direction. Triangular crystallites are observed in the surface topograph of the samples with Atomic Force Microscopy. Optical properties of the films were thoroughly investigated using optical absorbance, cathodoluminescence (CL) and photoluminescence (PL) spectroscopy. Room temperature absorption spectroscopy confirms the existence of two exciton peaks namely Z_{12} and Z_3 at 372 and 380 nm respectively. UV emission is observed at room temperature in CL and PL spectra by the decay of Z_3 exciton at around 383nm. The thermal broadening of the Z_3 exciton and temperature dependence of the excitonic band gap are investigated with PL spectroscopy at temperatures ranging from 10K to 300K.

EE3.23
Fabrication of Nitrided Mask on GaAs Surface and Its Machinability for STM Lithography. Yo Yamamoto[1], Toshiyuki Kondo[2], Sota Matsuoka[2], Takahiro Maruyama[2,1] and Shigeya Naritsuka[2,1]; [1]21st Century COE Program "NANOFACTORY", Meijo Univ., Nagoya, Japan; [2]Materials Science, Meijo Univ., Nagoya, Japan.

STM lithography is one of the attractive ways to fabricate nano structures for optical and electronic devices. To take full advantages of STM lithography, it is important to develop the applicable mask with thermal stability and good machinability. We studied the formation of GaN thin layer on GaAs (001) substrates by RF-MBE, and previously presented controllability of the flatness with process factors, such as substrate temperature [1]. In this study, we focus on machinability in STM lithography of the nitrided mask by controlling crystallinity with effective process factors, such as substrate temperature. After chemical etching with a solution of NH_4OH: H_2O_2: H_2O = 4:1:20, GaAs (001) substrate was heated up to 580°C in a MBE chamber to remove the native oxide layer. GaAs epitaxial buffer layer was deposited before nitridation in order to form a flat surface. To prevent As evaporation the As flux was supplied at 1.1×10^{-3}-3.2×10^{-4}Pa until nitridation. Then, the surface of the GaAs layer was nitrided using RF nitrogen source changing substrate temperature between 300 and 320 °C. Comparison of RHEED patterns indicated that the surface nitrided at 300°C had lower crystallinity, since the pattern was scattered, while the surface nitrided at higher temperature, i.e. at 320°C, showed higher crystallinity since its pattern had a facet structure. It was also found that the nitridation at lower temperature caused weak Ga-N bond from the result of XPS profiles. By STM lithography the sample nitrided at 300°C was cut in 20nm2 at the bias voltage of 80V, while the sample nitrided at 320°C was cut at higher voltage of 150V. So, it is concluded that the substrate nitrided at lower temperature gives better machinability for STM lithography. Ref. [1] Y. Yamamoto, Mat. Res. Symp. Proc. 843 (2005), T3.5

EE3.24
Annealing Time Dependence on 1.5μm Photoluminescence of Laser-Ablated β-FeSi$_2$. Kunitoshi Aoki, Mohammad Zakir Hossain, Shin-ichiro Uekusa, Tomohiro Fukuda and Noboru Miura; School of Science and Technology, Meiji University, 1-1-1 Higashi-mita, Tama-ku, Kawasaki-shi, Kanagawa-ken, Japan.

Semiconducting β-$FeSi_2$ is composed with nontoxic elements, which exist in great abundance on earth, and has possibility of emission around 1.5 μm. Therefore, β-$FeSi_2$ is expected in environmental friendly Light-Emitting-Diodes (LED) for optical fiber communications. In addition, β-$FeSi_2$ thin-films can grow epitaxially on silicon substrate, because of its crystal lattice constant which is nearly equal that of silicon. However no photoluminescence from laser-ablated β-$FeSi_2$ thin-films were obtained. So, we have studied the relation between crystal quality and optical property on laser-ablated β-$FeSi_2$ thin-film crystal. We prepared β-$FeSi_2$ thin-films on Floating-Zone (FZ) n-Si (111) substrate at 500 °C of substrate temperature with ArF excimer-laser and $FeSi_2$ (99.99%) sintered target. Long-time and high-temperature thermal annealing was performed after the deposition in order to improve the crystal quality. Samples were annealed with infrared lamp under nitrogen atmosphere. Annealing times are 5, 10, 20 and 40 hrs, and annealing temperatures are respectively 600, 700, 800 and 900 °C. Crystallinity was evaluated by X-ray Diffraction (XRD) measurement. We have observed effective crystal-quality of β-$FeSi_2$ because the Full Width at Half Maximum (FWHM) is 0.27°. We have succeeded to observe photoluminescence around 1.5 μm corresponding to β-$FeSi_2$ bands from the long-time and high-temperature annealed β-$FeSi_2$ thin-films. We will report and discuss the relationship on photoluminescence spectra and crystal quality in systematically experiments.

EE3.25
Crystal structure and physical properties of GaSe single crystals annealed in sulfur atmosphere. Olga V. Voevodina[2], Aleksandr N. Morozov[2], Sergey Yu. Sarkisov[2], Nils C. Fernelius[1] and Jonathan T. Goldstein[1]; [1]Materials & Manufacturing Directorate, Air Force Research Laboratory, Wright-Patterson AFB, Ohio; [2]Siberian Physico-Technical Institute, Tomsk, Siberia, Russian Federation.

Gallium selenide remains one of the promising crystals for near and middle IR-range nonlinear optics. Recently it has also been shown that large high-quality GaSe crystals can be used for the creation of millimeter and submillimeter (THz) coherent radiation sources. High-quality crystals grown by the latest technology are characterized by low values of optical loss. In the maximal transparencyrange, 1.5-12 μm, the absorption coefficient values lie within 0.1-0.05 cm(-1). Such values are typical for the crystals grown at the Siberian Physico-Technical Institute. However, additional advances in the crystal's material properties are needed before GaSe achieves its full potential technological impact. Specifically, it is desirable that a method be found for increasing the crystal's hardness, thereby reducing the crystal's tendency to microspall. This would allow the crystal to be cut at angles arbitrarily related to the growth plane, in order to achieve higher optical conversion efficiency. Thus, the study of modifying the crystal properties by various doping and post-growth treatments, is still an area of ongoing active research. In this work we studied the influence of annealing in sulfur vapor and in vacuum on the properties of GaSe single crystals. The objective of this work was

the study of the possibility of intercalating GaSe with sulfur from the gas phase, and to compare the influence of doping with sulfur from the melt and vapor phase on the structure and properties of GaSe crystals. Three series of annealing experiments have been conducted at temperatures 773, 923, 1073 K. The obtained samples have been studied by Hall effect, photoconductivity, optical absorption, microhardness measurements, and X-ray diffractometry. A thermodynamic analysis of the interaction between GaSe crystals with sulfur vapor indicates a high probability of Ga2S3 and GaS compound formation. X-ray measurements show that the system has a very strong tendency to form a Ga2S3 film on the crystal surface. This was observed in almost all samples studied. However, X-ray measurements of vacuumed annealed samples reveal an increase in peak intensities. Apparently, annealing GaSe crystals in vacuum promotes crystalline perfection. Electrophysical measurements of melt-doped crystals show behavior similar to that of those annealed in sulfur vapor. After annealing in sulfur vapor the carrier mobility decreases. The resistance of the samples annealed at temperatures 773 K decreases, but samples annealed at higher temperatures show an increase in microhardness. Sulfur doping caused a peak to appear in the photoconductivity spectra near the intrinsic band. Within the intrionsic band two peaks corresponding to the band gaps of GaSe and Ga3Se3 have been revealed. We also present a hypothesis to explain the impact of diffusion doping and melt doping with sulfur on the crystal structure and physical properties of GaSe crystals.

EE3.26

Analysis of the Temperature Diffusion Length in High Power InGaAs/GaAs Lasers. Tomasz J. Ochalski, Dorota Wawer, Kamil Pierscinski, Anna Szerling, Michal Szymanski and Maciej Bugajski; Institute of Electron Technology, Warszawa, Poland.

In this work we present the analysis of thermal properties of high power InGaAs/GaAs lasers. The temperature distribution within the laser is studied both experimentally and theoretically. The spatially resolved thermoreflectance technique is used to obtain a detailed temperature distribution maps of the working devices. Such a method gives temperature maps with a spatial resolution better than 1μm. The absolute temperature of different parts of the laser is determined with accuracy of 1°C. The mapped area is the laser facet; i.e. the active region of the device and the substrate. We have examined series of lasers with different contact width and otherwise the same construction and the same cavity length. Major point of this work is comparison of the temperature distribution within devices with different contact width; starting with the narrow stripe and ending with broad area lasers. We compare thermal properties and specifically temperature diffusion lengths in the lasers with stripe width of 5, 10, 20, 40 and 80 μm. Numerical calculations of temperature distributions in the devices studied are performed by finite element method (FEM) method. The paper addresses an important subject of device design optimization. Up to now there are only few theoretical papers on temperature diffusion length in semiconductor lasers. As far as experimental determination of the temperature distribution in the lasers is concerned there is no other method than thermoreflectance, which can give comparable accuracy and spatial resolution. The method developed in our laboratory proved to be a perfect tool to determine real temperature distribution within working laser diode.

EE3.27

Evaluation on Defects of Er Implanted $Al_{0.70}Ga_{0.30}As$ by Using Positron Annihilation Spectroscopy. Tomoyuki Arai[1], Shin-ichiro Uekusa[1] and Akira Uedono[2]; [1]Dept. of Electrical and Electronic Engineering, Meiji Univ., Kawasaki, Kanagawa, Japan; [2]Institute of Applied Physics, Tsukuba Univ., Tsukuba, Ibaraki, Japan.

Erbium (Er)-doped semiconductors are of much interest as an application of optical emitting device at 1.54 μm, which coincides with the wavelength of minimum loss in silica-based optical fiber. It is important for the Er-doped semiconductor to improve problems such as poor luminescence intensity and the rapid thermal quenching property of the Er-related emission of energy transition from the host semiconductor to intra-4f-shell of Er ions. So far, Er ions were implanted into $Al_{0.70}Ga_{0.30}As$ substrates; we have studied on the optical properties of Er intra-4f-shell luminescence. These substrates were grown un-doped $Al_{0.70}Ga_{0.30}As$ layer on GaAs (100) by Metal Organic Chemical Vapor Deposition (MOCVD). In this work, we studied the optical sensitization and the defects of Er implanted $Al_{0.70}Ga_{0.30}As$ substrates. Er implantation was carried out at 1MeV with doses of 1 x 10^{-13} cm^{-2} at RT. After implanting the ions, these samples were thermal annealed at temperature of 800 °C for 10min by the face-to-face technique in hydrogen atmosphere. The influence on defects of Er implanted $Al_{0.70}Ga_{0.30}As$ was studied, using standard Positron Annihilation Spectroscopy (PAS) and Photoluminescence (PL) technique. The incident energy of mono-energetic positrons was implanted from 0.1 eV to 30 keV. The characterization of un-doped $Al_{0.70}Ga_{0.30}As$, $Al_{0.70}Ga_{0.30}As$:Er as implanted, and $Al_{0.70}Ga_{0.30}As$:Er annealed at 800 °C were successfully studied by using PAS technique. Into the incident energy around 5keV, Shape parameter of $Al_{0.70}Ga_{0.30}As$:Er annealed at 800 °C was nearly equal to un-doped $Al_{0.70}Ga_{0.30}As$. We report systematically the experimental results of PAS as being related to PL.

EE3.28

Solid-State Microwave Synthesis and Magnetic Properties of Semiconductors Based on the I-III-VI_2 System. Jonathan William Lekse, Anna M. Pischera, Molly L. Gahan, Heather A. Figore and Jennifer A. Aitken; Chemistry and Biochemistry, Duquesne University, Pittsburgh, Pennsylvania.

Diluted magnetic semiconductors (DMS) such as GaAs:Mn have a crystal structure based on that of diamond and exhibit magnetic and electrical properties that render them promising for a number of applications such as spintronic devices. There are two principle challenges that arise during the synthesis of new DMS, which have so far prevented these materials from realizing their potential. The first difficulty is the incorporation of a sizable amount of magnetic ion into the structure. The other issue is that the Curie Temperature, T_c, should be near or above room temperature in order for the material to have practical device applications. In an attempt to address these obstacles, we have chosen to focus our work on more complicated ternary systems that are based on the structure of cubic diamond. Theoretical work has suggested that p-type I-III-VI_2 systems should exhibit ferromagnetism at practical temperatures when doped with Mn. Preparation and characterization of these materials is a difficult task. Traditional high-temperature, solid-state synthetic methods can easily lead to phase separation due to the high probability of thermodynamic sinks. Certain soft techniques, which proceed far from thermal equilibrium, often yield non-homogenous materials in which it is difficult to ascribe the observed magnetic behavior to a specific composition. Therefore, we have chosen to pursue the underutilized, solid-state microwave synthetic method. This method has been used to successfully prepare a variety of materials. This talk will focus on the microwave preparation of $AgInSe_2$, $AgInSe_2$:Mn, $CuInSe_2$ and $CuInSe_2$:Mn. These materials have been prepared by the microwave irradiation of the elemental starting materials in fused-silica vessels that were sealed under vacuum. The resulting materials have been structurally and physiochemically characterized. In particular, magnetic susceptibility data will be discussed.

EE3.29

$InAs/In_{0.15}Ga_{0.85}As_{1-x}N_x$ quantum dots for 1.5 μm laser applications. Mirja Richter[1,2], Benjamin Damilano[1], Andreas D. Wieck[1,2], Jean-Yves Duboz[1] and Jean Massies[1]; [1]Centre de Recherche sur l'Hetero-Epitaxie et ses Applications, Centre National de la Recherche Scientifique, Sophia-Antipolis, France; [2]Lehrstuhl fuer Angewandte Festkoerperphysik, Ruhr-Universitaet Bochum, Bochum, Germany.

It was recently demonstrated that using $InAs/In_{0.15}Ga_{0.85}As$ quantum dots (QDs) is an efficient way to achieve high performance lasers at 1.3μm on GaAs substrates. This is mainly related to three specific characteristics of such QDs: i) a low size dispersion (leading to a narrow photoluminescence emission); ii) a high density; iii) a coherent strained state (i.e. without dislocations). All these conditions have to be fulfilled to realize performant QD lasers. In an attempt to extend the wavelength emission in the 1.5μm range, several approaches have been proposed. In particular, embedding the InAs QDs in an InGaAsN/GaAsN matrix allows to achieve 1.5μm emission[1], but in this case, the PL full width at half maximum (FWHM) is considerably broadened compared to InAs/InGaAs QDs. The main objective of this work is to obtain QDs emitting in the 1.5μm range with a PL linewidth and intensity comparable to those achieved with $InAs/In_{0.15}Ga_{0.85}As$ QDs emitting at 1.3μm. We studied InAs QDs overgrown by $In_{0.15}Ga_{0.85}As_{1-x}N_x$. The primary interest of this approach is that it allows us to grow InAs QDs on GaAs surface with a high density and a narrow size dispersion (obviously the same as for InAs QDs encapsulated by InGaAs). Also, the $In_{0.15}Ga_{0.85}As_{1-x}N_x$ alloy has a lower bandgap energy than $In_{0.15}Ga_{0.85}As$ and is better lattice matched with GaAs, both elements being of key importance to get longer wavelength emission while avoiding dislocation formation. Nevertheless, the material quality of InGaAsN remains problematic as it is affected by a lot of point defects due to low growth temperatures and it needs annealing to reach optimum PL efficiency. We report on results obtained by growing self-assembled InAs QDs encapsulated with $In_{0.15}Ga_{0.85}As_{1-x}N_x$ by solid source molecular beam epitaxy. The growth temperature and rate were optimized separately for each of the layers, and the growth was interrupted after the QD growth in order to change and stabilize the temperature. The growth temperature was set at 520°C for InAs QDs, whereas it was varied from 420 to 480°C for InGaAsN layer. High QD densities of about $4{\cdot}10^{10}$ cm^{-2} are obtained for all samples. The PL wavelength red-shifts from 1.32 to 1.52μm when the N composition increases from 0 to 0.017. However,

this shift is correlated to a decrease in PL intensity. Rapid thermal annealing realized at different temperatures partially compensates this reduction. For a structure with 1.2% N, room temperature integrated PL intensity indicates that only a factor 3.0 is lost compared to an $InAs/In_{0.15}Ga_{0.85}As$ QD reference and the PL FWHM is 38.9meV. These results constitute a step towards the achievement of QD lasers on GaAs substrates emitting at 1.5μm. [1] V.M. Ustinov, A.Y. Egorov, V.A. Odnoblyudov, N.V. Kryzhanovskaya, Y.G. Musikhin, A.F. Tsatsul'nikov, and Z.I. Alferov, J. Cryst. Growth 251, 388 (2003).

EE3.30
Formation of Substrate-independent Conductive Distributed Bragg Reflector by Annealing Low-temperature-grown Alternating Amorphous (Ga, As) /(Al, As) Layers.
Chaofeng Xu[1], Hung-Cheng Lin[2], Zhenhua Zhang[1], Kuo-Lih Chang[3], John Epple[4], Keh-Yung Cheng[1] and Kuang-Chien Hsieh[1]; [1]Department of Electrical and Computer Engineering, and Micro and nanotechnology Laboratory, University of Illinois at Urbana-Champaign, Urbana, Illinois; [2]OptiComp Corporation, Zephyr Cove, Nevada; [3]Applied Materials Inc., Sunnyvale, California; [4]Intel Corporation, Hillsboro, Oregon.

Semiconductor stacks having alternating refractive indices have been commonly used to form distributed Bragg reflector (DBR) and surface emitting lasers. Challenges arise when the single crystalline DBR stacks have a lattice constant significantly different from that of the active region. Although amorphous materials such as oxides can be used to form DBRs without the lattice constraint, they are not conductive so current injection through the DBRs is not possible. We propose to fabricate such conductive yet substrate independent DBRs by annealing low-temperature-grown (LT) amorphous (Ga,As)/(Al,As) stacks In our work, alternating layers of amorphous (Ga, As) and (Al, As) layers are deposited on crystalline GaAs or InP wafers at around 100 ^{o}C in an MBE chamber. A 20-pair amorphous (Ga, As) and (Al, As) DBR designed for wavelengths in the 1.3-1.5 μm range exhibits reflectivity as high as 99%. Upon annealing in a nitrogen ambient at about 400 ^{o}C for 2 minutes, the amorphous (Ga, As) and (Al, As) become polycrystalline as determined by cross-sectional transmission electron microscopy. Reflectivity measurements show that the annealed DBR reflects lights having wavelengths between 1-1.2 μm up to 97%. The shift in reflectivity spectrum is due to the size reduction of amorphous (Ga,As)/(Al,As) layers when crystallized upon annealing. In addition, in the polycrystalline (Ga,As) or (Al,As) layers excess As form an As precipitate network resulting in conducting p-type semiconductors.

EE3.31
Magnetic and Optical Properties of I-III-VI_2:Mn and I_2-II-IV-VI_4 Diamond-Like Semiconductors. Jennifer A Aitken[1], Jonathan W Lekse[1], Katie L. McNerny[1], Anna M. Pischera[1], Heather A. Figore[1], Kang M. Ok[2] and P. Shiv Halasyamani[2]; [1]Department of Chemistry and Bichemistry, Duquesne University, Pittsburgh, Pennsylvania; [2]Department of Chemistry, University of Houston, Houston, Texas.

Although most of the research involving diamond-like semiconductors (DLS) has focused on simple, binary III-V, IV-IV and II-VI systems, ternary and quaternary DLS are also interesting, due to their potential uses in many fields such as non-linear optics and spintronics among others. In order to be considered a diamond-like material, a number of rules must be satisfied. For example, the average valence electron count must equal four and the number of valence electrons per anion must be eight. In addition, Pauling's first and second rules should be satisfied. Therefore, the number of formulae for diamond-like compounds is finite; however, the number of possible compounds is quite large, especially when considering the possibilities of solid solutions. Ternary and quaternary systems are often more difficult to synthesize than their binary relatives; however, they add additional compositional flexibility, which can be exploited in order to tune properties, for instance bandgap engineering. This talk will describe the rapid, solid-state microwave preparation of ternary I-III-VI_2 compounds as well as I-III-VI_2:Mn materials, such as $CuInSe_2$:Mn and the traditional, solid-state preparation of quaternary I_2-II-IV-VI_4 materials, such as Li_2CdGeS_4, at high temperature. Powder X-ray diffraction, scanning electron microscopy, energy dispersive spectroscopy, differential thermal analysis, diffuse reflectance spectroscopy as well as second harmonic generation of these diamond-like materials will be presented. Additionally, magnetic susceptibility data of doped materials will be discussed.

EE3.32
Electrical activation of carbon-doped GaAs/AlGaAs layers annealed under different dielectric layers. Paulus Lobo Gareso, Lan Fu, Manuela Buda, Hark Hoe Tan and Chennupati Jagadish; Electronic Materials Engineering, The Australian National University, Canberra, Australian Capital Territory, Australia.

Carbon is used as p-type dopant in GaAs/AlGaAs structures due to its lower diffusivity than zinc which make it more suitable for applications that involve high temperature processing steps (usually >900oC). Previous study of carbon-doped samples in the InGaAs/AlGaAs laser structures has shown that carbon was electrically activated after annealing at 900oC in uncapped samples, and there was an increase in the amount of lattice contraction associated to the presence of substitutional carbon CAs. This was attributed to the outdiffusion of arsenic from the sample surface (in uncapped samples) to promote the carbon atoms to sit in the As vacancy sites and hence becoming activated. In the present study, we investigate the activation of carbon dopant in the GaAs and Al0.6G0.4As samples annealed under different dielectric capping layers (SiO2, SiN and TiO2). In some cases, a reduction in the carrier concentration was obtained while in other, an increase in activation was observed. We will discuss these results in relation to the outdiffusion of As, interfacial reaction and the associated strain affect due to the difference in the thermal expansion coefficients between the capping layers and the semiconductors.

SESSION EE4: Teraherz Materials and Devices
Chairs: Linda Olafsen and Michael Wanke
Tuesday Morning, November 29, 2005
Constitution B (Sheraton)

8:00 AM EE4.1
MOVPE grown QCLs emitting at 7.6μm and 10.3μm.
Andrey Krysa[1], J. S. Roberts[1], C. M. Tey[1], R. P. Green[2], L. R. Wilson[2], E. A. Zibik[2], D. G. Revin[2], J. W. Cockburn[2], C. Pfluegl[3], W. Schrenk[3] and G. Strasser[3]; [1]EPSRC National Centre for III-V Technologies, Dept. of Electronic and Electrical Eng., University of Sheffield, Sheffield, United Kingdom; [2]Dept. of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom; [3]Zentrum fuer Mikro- und Nanostrukturen, Technische Universitaet Wien, Vienna, Austria.

AlInAs/InGaAs/InP quantum cascade lasers (QCLs) are compact semiconductor light sources for the mid-infrared spectral region. The established technology of MBE is generally used to fabricate the many hundreds of very thin layers, which comprise the gain region in such devices. However, recently, we reported the MOVPE growth of AlInAs/InGaAs/InP QCLs emitting at $\sim$9μm [1, 2]. MOVPE is more suited to epitaxy requiring InP substrates, as well as higher growth rates and the scaling to multi-wafer deposition. Furthermore, these MOVPE grown QCLs are analogous to InP based telecom wavelength lasers, which are manufactured predominately by MOVPE. The presentation will report the growth and performance of Fabry-Perot (F-P) and distributed feedback (DFB) QCLs emitting at 7.6μm and 10.3μm. These wavelengths are of particular interest to optical sensing of methane and ethane, respectively. The QCL design utilizes a four-well active region or double-phonon resonance design [3] to optimize the depopulation of the lowest energy level in each of the 35 cascaded gain sections. (004) X-Ray diffraction was used to determine the period of the gain sections. The measured values were within 2% of the intended thickness showing a high degree of thickness control, which is required for reproducible lasing wavelengths. In addition, TEM indicated resolved AlInAs/InGaAs layers, including the very thin (nominal thickness of 8$\AA$) barriers of the 7.6μm laser. 7.6 and 10.3 micron F-P ridge wave-guide lasers with 1.3mm long cavities were operated in pulse mode with respective RT threshold currents of $J_{th}\sim$2.9 kA cm^{-2} and 3.3 kA cm^{-2}. All samples lased above RT and as high as 320K, only limited by the cryostat temperature range. QCLs operating with a single longitudinal mode are required for spectroscopic applications and have therefore been patterned with λ/2n DFB gratings. A close alignment of the peak in the gain spectrum with the DFB grating has resulted in reduced threshold currents of 2.4kA cm^{-2} and 3kA cm^{-2} for the 7.6 and 10.3 micron devices respectively. The peak power output of the DFB devices was $\sim$0.4W at RT. 1. R.P.Green et al, Appl. Phys. Lett. 83 (2003) 1921 2. A.B.Krysa et al, J. Cryst. Growth 272 (2004) 682 3. M.Beck et al, Science 295 (2002) 301

8:15 AM *EE4.2
New approaches for short wavelength quantum cascade lasers.
Luke Wilson[1], Dmitry Revin[1], Matthew Steer[2], Evgeny Zibik[1], John Cockburn[1], Robert Airey[2] and Mark Hopkinson[2]; [1]Physics and Astronomy, University of Sheffield, UK, Sheffield, United Kingdom; [2]National Centre for III-V Technologies, University of Sheffield, Sheffield, United Kingdom.

High performance, mid-infrared quantum cascade lasers (QCLs) emitting at wavelengths beyond 5μm have reached a high level of technological maturity over recent years. Attention is now turning to producing QCLs with similar levels of performance operating in the technologically important $\lambda\sim$3$-$5μm atmospheric window. In order to

push QCL emission down to 3μm and beyond it is highly desirable to use heterostructure materials with the largest possible conduction band offset (ΔE_c), as this determines the ultimate limit on short wavelength QCL operation. I will begin by comparing recent results and predicted performance levels for the most promising high ΔE_c materials systems for short wavelength QCLs, namely (i) strain compensated InGaAs/AlInAs on InP substrates, (ii) lattice matched (or strain compensated) InGaAs/AlAsSb on InP and (iii) InAs/AlSb on either InAs or GaSb. I will then discuss in detail our recent work, in which we have extended the QCL concept to the $In_{0.53}Ga_{0.47}As$-$AlAs_{0.56}Sb_{0.44}$ materials system which combines a very large ΔE_c ($\sim$1.6eV) with straightforward integration into existing, well-established InP-based waveguides and fabrication technology. Due to the high complexity of QCL design and the stringent demands placed on layer thickness control and uniformity, extension to this materials system presents a considerable challenge. However, our QCL performance levels as well as optical and structural characterisation indicate high quality epitaxial growth with minimal Sb segregation, providing strong confidence in this approach for high performance QCLs operating in the 3-5μm region. [1] D.G. Revin, L.R. Wilson, E.A. Zibik, R.P. Green, J.W. Cockburn, M.J. Steer, R.J. Airey and M. Hopkinson, Appl. Phys. Lett. 84, 1447 (2004). [2] D.G. Revin, L.R. Wilson, E.A. Zibik, R.P. Green, J.W. Cockburn, M.J. Steer, R.J. Airey, and M. Hopkinson, Appl. Phys. Lett. 85, 3992 (2004). [3] D.G. Revin, M.J. Steer, L.R. Wilson, R.J. Airey, J.W. Cockburn, E.A. Zibik, R.P. Green, Electron. Lett. 40, 874 (2004).

8:45 AM *EE4.3
Terahertz Dynamical Conductivity in Bloch Oscillating Semiconductor Super-Superlattices. S. James Allen[2,1], Pavlos G. Savvidis[2,5], Borys Kolasa[1], Shigeki Kobayashi[2,4], Peter Robrish[3], Greg Lee[3] and Dan Mars[3]; [1]Physics Department, UCSB, Santa Barbara, California; [2]Institute for Quantum and Complex Dynamics, UCSB, Santa Barbara, California; [3]Agilent Laboratories, Palo Alto, California; [4]IIS, University of Tokyo, Tokyo, Japan; [5]Physics Department, University of Crete, Heraklion, Greece.

Bloch oscillation in electrically biased semiconductor superlattices offers potential broadband terahertz gain from DC up to the Bloch frequency or Stark splitting. Useful gain up to 2-3 terahertz can be the basis for fundamental solid-state electronic oscillators operating at 10 times the frequency of existing devices. Here we describe recent experiments that directly measure terahertz "loss and gain" in electrically biased super-superlattices and project its use in terahertz oscillators. The earliest theoretical models of electrically biased superlattices predicted an unusual dynamical conductivity; the absorptive part was predicted to be negative, exhibiting gain, at frequencies up to the Bloch frequency at which point it is expected to cross over and exhibit loss. A device based on this phenomenon may be described as a terahertz laser with out inversion. Various experiments have demonstrated Bloch oscillation in semiconductor superlattices. Only recently have measurements been carried out that directly measure the dynamical terahertz conductivity under electrical bias. A major stumbling block is the inherent instability of the electrically biased doped superlattice to the formation of electric field domains. To circumvent this, we have fabricated super-superlattices. We anticipate that space charge is swept out of the short superlattice between heavily doped regions before it can establish an electric field domain wall. Room temperature, terahertz photon assisted transport in a variety of test structures comprised of 1, 2 and 5 short superlattice cells of an InGaAs/InAlAs super-superlattice allows us to determine the Stark ladder splitting and confirms the absence of electric field domains in short structures. The absorption of radiation from 1.5 to 2.5 THz is measured in 10 micron high InAs/AlSb superlattices, punctuated with heavily doped regions. Under electrical bias the super-superlattices exhibit a crossover from loss to gain as the Stark ladder is opened and the spacing of the rungs exceeds the measurement frequency. These room temperature measurements are carried out in a novel planar terahertz waveguide defined by photonic band gap sidewalls and loaded with an array of electrically biased super-superlattices. The terahertz frequency dependent crossover voltage indicates $\sim$ 80% participation by the super-superlattice. We conclude by proposing Bloch oscillator terahertz waveguide structures that can use the available gain to make an electronic solid-state fundamental terahertz coherent oscillator. UCSB work has been supported by ARO, DARPA/ONR and CNID.

9:15 AM EE4.4
Room temperature tunable resonant detection of terahertz radiation by nanometer high electron mobility transistors. Dmitry Veksler[1], Frederic Teppe[1,2], Valentin Yu. Kachorovski[1,3], Alexandre P. Dmitriev[1,3], Xu Xie[1], Xi-Cheng Zhang[1], Sergey Rumyantsev[1], Wojtek Knap[1,2] and Michael S. Shur[1]; [1]Rensselaer Polytechnic Institute, Troy, New York; [2]GES CNRS-Universite Montpellier 2 UMR 5650 34900, Montpellier, France; [3]A.F. Ioffe Physical-Technical Institute, Saint Petersburg, Russian Federation.

We report on the resonant detection of terahertz radiation by nanometer High Electron Mobility Transistors (HEMTs) at room temperature. Our results show that field effect transistors with nanometer size gates can be used as tunable and fast terahertz detectors with a large signal-to-noise ratio. The resonant detection occurs when the frequency of electron concentration oscillations in the FET channel (called plasma waves) is larger than the inverse plasma oscillations decay time. The detection responsivity depends on the asymmetry in the boundary conditions for plasma waves. This asymmetry can be strongly enhanced by applying a drain-to-source bias. Even more importantly, the plasma decay time can be greatly increased by operating the transistor in the saturation regime, where the electron velocity in the device channel is high. In the resonant case, the detection amplitude has maxima, when the radiation frequency is equal to fundamental plasma frequency and its harmonics. Our theory predicts that the effective line widths of the respective resonances would decrease with the increasing electron drift velocity (or drain current). At some critical current value, the width corresponding to the fundamental frequency would turn to zero, indicating the onset of the plasma wave generation. This should result in the generation of terahertz radiation, and this effect is now under investigation. The experimental measurements were performed using nanometer-size GaAs HEMT and Si SOI transistors. 0.2 THz and 0.6 THz Gann diodes served as radiation sources. The resonant detection of 0.6 THz radiation was observed for 250 nm GaAs HEMTs. The responsivity strongly increased and became resonant when the transistor was driven into the current saturation region. The detector response to 0.2 THz radiation increased by almost two orders of magnitude with increasing drain current, however, it did not become resonant. The interpretation of the results as due to plasma wave detection enhanced by increasing the electron drift velocity was found to be in good agreement with the predictions of the plasma wave detection theory. The experimental evidence of the resonant plasma wave detection of femtosecond pulsed terahertz radiation obtained by optical rectification in a ZnTe crystal (one of most important sources in modern terahertz spectroscopy) was also demonstrated using the same 250 nm gate length GaAs/AlGaAs HEMT. The results show that plasma wave nanometer transistors can be efficient and fast detectors for terahertz spectroscopic applications.

9:30 AM EE4.5
Plasmon Based Split-Grating-Gate Terahertz Detector. Eric A. Shaner[1], Mike C. Wanke[1], John L. Reno[1], Mark Lee[1], Albert D. Grine[1] and S. James Allen[2]; [1]Sandia National Labs, Albuquerque, New Mexico; [2]Center for Terahertz Science & Technology, UC Santa Barbara, Santa Barbara, California.

Single and Double quantum well grating gate detectors have recently emerged as a widely tunable detector of millimeter wave to THz radiation. A typical device consists of source and drain contacts along with a single grating gate which both modulates the carrier density and couples in the free space radiation to the plasmon modes of the quantum well heterostructure. Through a simple change in the basic gate design we have intentionally introduced an additional non-linearity into the device. Through proper biasing of this new structure, we are able to increase the responsivity of the basic grating gate detector by three orders of magnitude, into the few V/W range, while maintaining the tunable aspects of the original device. This talk will describe the new non-linear aspects of these detectors, along with the wavelength tunability and temperature dependence of the photoresponse. 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. Work at UCSB is supported by the ARO.

9:45 AM EE4.6
Spectral and Temporal Resolution of THz Detectors Based on Quantum Hall Devices with Various Geometries. Nikolai G. Kalugin[1], Christian Stellmach[2], Alex Hirsch[2], Yuri Vasilyev[4], Guenter Hein[3], B. Erol Sagol[3] and Georg Nachtwei[2]; [1]Department of Physics, Texas A&M University, College Station, Texas; [2]Instutute of Applied Physics, TU-Braunschweig, Braunschweig, Germany; [3]Physikalisch-Technische Bundesanstalt, Braunschweig, Germany; [4]A. F. Ioffe Physical Technical Institute, St.-Petersburg, Russian Federation.

Measurements of the THz photoconductivity at quantum Hall systems (QHS) are interesting with respect to the application of QHS as sensitive and tunable THz detectors for wavelengths around 100 micrometers. In this study, we present measurements of the photoconductivity at QHS using pulses of THz p-Ge laser radiation in the region of 1.7 to 2.5THz. The QH samples used for this study were a meander sample, and a circular Corbino device, patterned photolithographically from GaAs/GaAlAs-heterostructures with a two-dimensional electron system. The wafer which the meander and Corbino samples are patterned from has an electron density of

2x1011cm-2 and mobility of approx. 500000 cm2/Vs. From our time-resolved measurements we distinguished bolometric and cyclotron-resonant contributions to photoconductivity. The bolometric part is due to non-resonant excitation, and dominates at magnetic fields near the flanks of QH plateaus. Cyclotron resonance occurs for the coincidence of the Landau level splitting with the photon energy. Reversing the magnetic field direction, we were able to separate alterations of the longitudinal resistance from changes of the Hall signal due to changes of the Hall resistance and THz-induced Hall currents. The transversal part of the photoresponse (PR) in meander devices decays during 5-10 microsec. There are also parts of the PR with long decay times (t > 280 microseconds). These parts are only longitudinal ones. In this work, we report on our measurements of the spectral resolution of the THz-QH-detectors. At constant laser wavelength the PR was measured as a function of the magnetic field B for constant filling factor. This requires a variation of the carrier concentration. The adjustment of concentration is realized by a backgate. We have found that the spectral resolution of the THz-QH detector is a function of the sample current. In general, the spectral resolution of the THz-QH detector improves with increasing sample current. In the meander samples, the Hall-related part of the signal was found showing a faster decay than the longitudinal part. In Corbino devices, the photoinduced source-drain current corresponds topologically to the Hall current of the meander geometry. The time resolution of our setup allows us to observe fast relaxation times of the Corbino detector, from 20ns to 150ns. These time scales are several orders of magnitude shorter in comparison to data published at meander type detectors.

10:30 AM *EE4.7
Controlling Surface Plasmon Modes in Terahertz Quantum Cascade Lasers. Alessandro Tredicucci, NEST-INFM, Scuola Normale Superiore, Pisa, Italy.

Quantum cascade lasers (QCLs) operating in the mid infrared spectral range have proven their usefulness as a compact, powerful source of coherent radiation. Recently, the QCL concept was successfully extended to the terahertz range, thanks to the implementation of a waveguide concept based on surface plasmon propagation. The performances of these devices is rapidly improving, with pulsed operation reaching about 140 K. Their implementation in many applications in chemical recognition and remote sensing now requires the realization of lasers for specific emission frequencies and the possibility of having stable, reliable, single-mode output, preferably with a broad tuning range. We have realized superlattice-based lasers for specific sensing applications, emitting at frequencies from 4.8 THz down to 2.3 THz. 2.5 THz is a frequency of particular interest, with potential applications in OH monitoring. Lasers emitting at this wavelength have shown low threshold current densities of 75 Acm^{-2} and high continuous wave (cw) output powers. These performance have been achieved by using the surface plasmon waveguide concept with two buried highly doped semiconductor layers. This allows the possibility of controlling separately the boundary conditions of the surface plasmons on the two sides, thereby resulting in a better compromise between optical losses and confinement factor. We have also developed distributed feedback (DFB) lasers operating at 2.5 THz. These are realised by opening up a periodic array of slits in the Cr/Au metallisation on the top of the ridge. Since the optical mode does not exist where the metal layer is absent, each slit acts as a potential barrier for light propagation. If the slit width is sufficiently small, minimal scattering out of the waveguide mode occurs and distributed feedback laser action can be established. Single mode emission has been demonstrated over the full range of investigated temperature and injection currents. The same technique can be implemented in Fabry-Perot devices to realize high-reflection distributed mirrors. We have fabricated distributed Bragg mirrors by lithographically defining slits with a $\lambda/2$ period at one end of 2.5 THz laser ridges. An improvement in threshold current of about 15% is observed and high peak powers of more than 15 mW can be recorded in pulsed from one facet. While the demonstration of stable, single-mode emission should further accelerate the implementation of THz QC lasers in many spectroscopic applications (with particular relevance to astronomical and atmospheric sensing), it is also obvious that a broad tuneability is crucial in this field. We are exploring both external cavity set-ups and the use of acoustic waves as means to externally control the laser cavity resonance. Both are challenging propositions, but preliminary encouraging results show that indeed these schemes can be used to affect laser emission and that tuneable THz QC lasers are a future possibility.

11:00 AM *EE4.8
Terahertz Generation by Photomixing in Semiconductor/Metal Composites. Arthur Gossard[2,1] and Elliott R. Brown[1]; [1]ECE Department, UCSB, Santa Barbara, California; [2]Materials Dept., UCSB, Santa Barbara, California.

We describe recent advances in the performance of tunable coherent Terahertz sources based on photomixing in semiconductor/metal composite materials. While the earliest photoconductive mixers for Terahertz generation were based on low-temperature-grown GaAs, improved performance is achieved with composite materials incorporating epitaxial semi-metallic ErAs nanoparticles. The nanoparticles have been incorporated in both GaAs [1] and InGaAs [2] for tunable, coherent Terahertz generation at 0.9 and 1.5 micrometer photoexcitation wavelengths. We have produced both photoconductive and photovoltaic mixers. Dense arrays of nanoscale islands produce the rapid photocarrier recombination needed for efficient photoconductive mixing. Single layers of the nanoislands provide the enhanced tunneling needed to cascade high-speed photovoltaic generators in a recently demonstrated alternate route to Terahertz generation [3] . 1. Bjarnason JE, Chan TLJ, Lee AWM, Brown ER, Driscoll DC, Hanson M, Gossard AC, Muller RE. Appl. Phys. Letters 85, 3983 (2004) 2. Driscoll DC, Hanson MP, Gossard AC, Brown ER. Appl. Phys. Letters 86, 51908 (2005) 3. G H Dohler, F Renner, O Klar, M Eckardt, A Schwanhausser, S Malzer, D Driscoll, M Hanson, A C Gossard, G Loata, T Loffler and H Roskos. Semicond. Sci. Technol. 20, S178 (2005)

11:30 AM EE4.9
Gallium Selenide Single Crystals for THz Applications. Krishna C. Mandal, Sung Hoon Kang, Gerardo J. Pena, Michael Choi and R. David Rauh; EIC Laboratories, Inc., Norwood, Massachusetts.

The single crystal growth of large semi-insulating GaSe by vertical Bridgman technique using in-house processed zone refined selenium (Se) and high purity gallium (Ga) has been described. The grown crystals are highly efficient for broadband tunable THz sources (10-40 THz) and sensors (100 GHz-30 THz), biomedical diagnostics, biochemical and trace explosive vapor identification. The grown crystals (2.5 cm diameter and ~10 cm long) have demonstrated extremely promising characteristics with good optical quality (absorption coefficient $\leq$0.1 cm^{-1} in the spectral range of 0.62-18 μm), high dark resistivity ($\geq 10^9$ $\Omega\cdot$cm), wide band gap (2.01 eV at 300K), good anisotropic ($\|$ and $\perp$) electrical transport properties ($\mu_{e/h}$, $\tau_{e/h}$, and $\mu\tau_{e/h}$) and long term stability. The crystals have been characterized by x-ray diffraction (XRD), energy dispersive analysis by x-rays (EDAX), Raman spectroscopy, x-ray photoelectron spectroscopy (XPS), and low temperature photoluminescence (PL) measurements. Various chemo-mechanical etching and different steps involved in fabricating GaSe crystals for THz sources and sensors will also be presented.

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

1:30 PM *EE5.1/FF7.1
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 m$\Omega\cdot cm^2$ 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 EE5.2/FF7.2

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 EE5.3/FF7.3

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 ($x \leq 0.50$), pronounced phase separation predominated with relatively weak ordering degree. High Al concentration ($x \geq 0.65$) 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 EE5.4/FF7.4

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 EE5.5/FF7.5

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 EE5.6/FF7.6

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 EE5.7/FF7.7

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 EE5.8/FF7.8

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 EE5.9/FF7.9

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 EE6: Nanostructured Semiconductors and
Novel Materials and Devices
Chair: Robert Biefeld
Tuesday Afternoon, November 29, 2005
Constitution B (Sheraton)

1:30 PM EE6.1
Nano-patterned Growth of Ge Quantum Dots for Infrared Detector Applications. Christopher Chen, Hyung-jun Kim, Fei Liu, Song Tong, Kang L. Wang, Dongho Cha and Joo-young Lee; Electrical Engineering, University of California, Los Angeles, Los Angeles, California.

Quantum dot infrared photodetectors (QDIPs) have been studied widely for normal-incidence infrared detection. The 3D confinement provided by quantum dots allows for the elimination of gratings that are typically required for normal-incidence detection in quantum well infrared photodetectors (QWIPs). Furthermore, the growth of Ge dots on Si substrates offers the potential for integration with existing CMOS platforms. To date, however, Ge QDIPs have typically been grown epitaxially by Stranski-Krastonov growth – producing pancake-like dots with base dimensions of 50-100 nm, heights of 7-10 nm, and an aerial dot density of 10^9-10^{10} cm^{-2}. Such dots have poor lateral confinement, causing them to have non-ideal normal-incidence absorption characteristics, similar to quantum wells. In this work, we demonstrate infrared absorption in Ge dots with base dimensions of approximately 40 nm. These dots are grown using molecular beam epitaxy on pre-patterned Si substrates, with an aerial dot density of approximately 10^{11} cm^{-2}. The substrates are prepared by using diblock copolymers to create a nano-pattern on the substrate surface which is transferred to the substrate by dry etching. The size of this pattern determines the base dimensions of the Ge dots. After growth, these dots are then tested for their infrared absorption properties using Fourier Transform Infrared (FTIR) Spectroscopy. The normal-incidence absorption of the dots can be studied with FTIR by varying the polarization angle of the infrared light. We present FTIR absorption spectra for samples grown with various conditions – such as varying dot doping levels – and investigate the effects of different growth conditions on infrared absorption properties. We also report on the normal-incidence absorption characteristics of these dots by presenting absorption spectra for various polarization angles of infrared light.

1:45 PM EE6.2
InGaAs Quantum Dot Infrared Photodetectors Grown by Metal Organic Chemical Vapor Deposition. Lan Fu, Greg Jolley, Hark Hoe Tan and Chennupati Jagadish; Electronic Materials Engineering, RSPHYSSE, The Australian National University, Canberra, Australian Capital Territory, Australia.

The concept of using the intersubband absorption of infrared radiation has led to the development of quantum well infrared photodetectors (QWIPs) in the past decades. Quantum dot infrared photodetectors (QDIPs) are expected to show improved performance over their quantum well counterpart in detecting infrared signal due to the localised states in quantum dots. They respond to normal incidence photoexcitation (where quantum wells only absorb in-plane photoexcitation due to the polarisation selection rules) thus eliminating the need for angular incidence, gratings or reflectors. Moreover, the discrete nature of the bound energy states of the quantum dots is expected to inhibit phonon scattering and therefore increases carrier capture and relaxation times in the quantum dots. This so-called phonon bottleneck effect is very useful for detectors using intersubband absorption, since photoexcited carriers are less likely to be captured into the quantum dots or to relax to the ground state before being swept away as a photocurrent, leading to improved detectivity, better quantum efficiency and increased operating temperatures. In this work we will show the results of MOCVD grown InGaAs QDIPs. MOCVD grown quantum dots are inherently more difficult than the complementary technique of MBE due to the higher growth temperature required and the lack of mature in-situ monitoring techniques. Nevertheless, the results presented here will show that the performance of our QDIPs to be reasonable. Various schemes will be discussed in this talk to show how the device performance could be improved. By incorporating a quantum well surrounding the dots, the so-called dots-in-a-well (DWELL) structure, enables the tuning of the detection wavelength and the transition type (bound-to-bound, bound-to-continuum) by simply changing the well composition/thickness. This type of device would also be more efficient in terms of lowering dark current. Results from such device will be presented here and compared to the standard QDIPs.

2:00 PM EE6.3
A Novel InSb Photodiode Infrared Sensor Operating at Room Temperature. Koichiro Ueno, Edson Gomes Camargo, Yoshifumi Kawakami, Yoshitaka Moriyasu, Kazuhiro Nagase and Naohiro Kuze; Central Research Laboratory, ASAHI KASEI CORPORATION, Fuji, Shizuoka, Japan.

A novel microchip-sized InSb photodiode infrared sensor (InSb PDS) operating at room temperature is reported. Pyroelectric sensors are generally used for detecting human body motion. However, they require the use of can-packages to insulate the sensitive element from thermal disturbances and electro-magnetic noises. The existing InSb photodetectors are put to practical use with cooling systems to reduce the influences of the high intrinsic carriers around 2x$10^{16}$$cm^{-3}$. Although InAsSb heterojunction photodiodes operated at near room temperature have been reported [1], its responsivity at 300 K could be still low for practical device applications. We have developed a microchip-sized infrared sensor, with a plastic molded package, having performance high enough for applications such as mobile electronic equipments. The basic structure of InSb PDS was grown on a semi-insulating GaAs (100) substrate by a Riber MBE-49 system, starting with the epitaxial growth of a 1 μm n^+-InSb layer followed by a 1μm p^--InSb layer. A barrier layer of 20 nm $p^+Al_{0.17}In_{0.83}Sb$ was grown on p^--InSb layer. And then a 0.5μm p^+-InSb layer was grown as a top contact layer. The n-type and p-type dopants were Sn and Zn, respectively, and their concentrations were 7x$10^{18}$$cm^{-3}$ for the n^+layer, 6x$10^{16}$$cm^{-3}$ for the p^-layer and 2x$10^{18}$$cm^{-3}$ for the p^+layer. The AlInSb barrier layer was proposed by T. Ashley et al to suppress the Auger processes by decreasing the free carrier concentration below its equilibrium values [2]. Auger-suppressed non-equilibrium photodiodes suffer from 1/f noise, hence high detectivity(D*) could only be obtained at high frequencies [3]. To avoid 1/f noise, the InSb PDS was operated at zero bias (photovoltaic) mode to output an open-circuit voltage. We confirmed not only an increase in zero bias resistance but also photocurrent was increased with the use of the AlInSb barrier layer. In addition, to improve performance, 700 photodiodes arranged on a 600 x 600μm^2 chip were serially connected each other. The InSb PDS has a typical responsivity of 1,900 V/W and an output noise of 0.15 $\mu V/Hz^{1/2}$ at 300 K. A detectivity of 2.8x10^8 $cmHz^{1/2}/W$ has been obtained at room temperature. The InSb PDS is a promising device for various applications such as cellular phones, mobile personal computers and so on. [1] J. Kim, S. Kim, D. Wu, J. Wojkowski, J. Xu, J. Piotrowski, E. Bigan, and M. Razeghi, Appl. Phys. Lett, Vol.67, 2645 (1995). [2] T. Ashley, A. B. Dean, C. T. Elliott, C. F. McConville, G. J. Pryce, and C. R. Whitehouse, Appl. Phys. Lett, Vol. 59, 1761 (1991). [3] C. T. Elliott, N. T. Gordon, R. S. Hall, and T. J. Phillips, C. L. Jones and A. Best, Journal of Electronic Materials, Vol.26, No.6, 643(1997).

2:15 PM EE6.4
Conductivity of InAs Nanorods Grown in GaAs Via Holes. Kangho Lee[1], Aristo Yulius[2], Eric Hamon[3], David Janes[1] and Jerry Woodall[1]; [1]Electrical and Computer Engineering, Purdue University, West Lafayette, Indiana; [2]Department of Electrical Engineering, Yale University, New Haven, Connecticut; [3]LightSpin Technologies, Inc, Norfolk, Massachusetts.

Semiconductor nanowires have attracted much attention due to their unique electrical and chemical properties. They have been used as an active device component for transistors, memory devices, and chemical sensors. However, it still remains problematic to make good contacts and to establish well-defined interfaces to nanowires. In this study, 2-terminal devices were fabricated to characterize threading dislocations in MBE GaAs as 1-D nanowires. MBE n+-InAs layers on top and bottom of the 20nm GaAs layer were used to form ohmic contacts to threading dislocations. The device consists of three layers: a 50nm n+-doped top InAs layer, a 20nm undoped GaAs layer, and a 1000nm n+-doped bottom InAs layer that was deposited by MBE on a GaP substrate. Even though InAs is 11% lattice-mismatched to GaP, the bottom InAs layer has a smooth metamorphic surface on GaP, releasing lattice mismatch stress by the formation of $\sim10^{10}cm^{-2}$ threading dislocations. Consecutive growth of GaAs layer and top InAs layer also induces threading dislocations with comparable density. After patterning and MESA etching the sample, non-alloyed metal contacts were deposited on each layer. At low bias voltages, the

conductivity of this device is expected to be negligible, as indicated by Medici simulations, because of the high resistivity of the undoped and depleted GaAs, and the barrier height arising from the bandgap difference between GaAs and InAs. However, the measured I-V shows a linear characteristic, and the current density at 0.1V is about three orders of magnitude higher than the one from the simulation. This implies the existence of an additional conduction path. To investigate the characteristic of this conduction mechanism, variable temperature I-V measurements have been performed, and measured I-V data was converted to ln (I/T^2) vs. 1/T to extract the barrier height (~25meV) according to Schottky emission model. One possible explanation for this phenomenon is the existence of a 1-D band of energy states located near GaAs midgap at threading dislocations sites. To check the validity of this interpretation, STM measurements of single dislocations are currently being attempted on the GaAs surface without the top InAs layer. The results will be presented at the conference. However, recent AFM measurements on the GaAs surface show that there exist growth defects with an estimated density of $\sim 10^6 cm^{-2}$. The AFM images of the GaAs surface reveal that these defects are ~200nm diameter holes some of which penetrate through 20nm GaAs layer to the bottom InAs layer. Since these holes get filled with high conductivity InAs nanorods when the top InAs is deposited, the most likely explanation for observed enhanced conductivity at low bias is carrier transport via the InAs nanorods rather than by the dislocations. This is interesting in itself and worthy of discussion at the MRS meeting.

3:30 PM EE6.5
Enhancement of Si Solar Cells in the Uv using Si Nanoparticles as Top Cells. Munir H. Nayfeh[1], Mathew C. Stupka[1] and Mohamed S. Alsalhi[2]; [1]Physics, University of Illinois, Urbana, Illinois; [2]Department of Physics, King Saud University, Riyadh, Saudi Arabia.

We integrated ultra thin films of luminescent silicon nanoparticles as top cells in polycrystalline photovoltaic (PV) Si solar cells. We examined the efficiency with 1 and 2.85 nm blue and red luminescent nanoparticle films, under UV radiation at 254, 310, and 365 nm, and as a function of the thickness of the film. Our results point to a PV efficiency enhancement of ~ 30-38 percent in this UV range. Our measurements also show that the nanoparticle film does not affect the PV efficiency in the visible part of the spectrum. The results are explained in terms of down conversion of UV wavelengths to visible luminescence wavelengths with very high quantum efficiency, and transparency in the visible resulting from the wide bandgap nature of ultrasmall silicon nanoparticles. By topping the film with appropriate reflective optics, we believe we can achieve near 70 percent enhancement for UV applications.

3:45 PM EE6.6
High-efficiency Solar Cells by Novel Light Bending Using Textured Photonic Crystals. Lirong Zeng, Yasha Yi, Ching-yin Hong, Xiaoman Duan and Lionel C. Kimerling; DMSE, MIT, Cambridge, Massachusetts.

To break through the current challenge of insufficient absorption of long wavelength photons in Si solar cells, we have successfully developed a new light-trapping scheme that can enhance the optical path length by more than 104 times via using a textured photonic crystal structure as the backside reflector. Therefore, the quantum efficiency of the solar cell can be enormously enhanced. Our back reflector design combines reflection grating on the Si substrate with a distributed Bragg reflector (DBR), which can strongly bend the incident light almost parallel to the surface of the absorption layer with a very high reflectivity (as high as 99.98%). New Si solar cells integrated with the novel back reflector are successfully fabricated and characterized. Double side polished thin crystalline Si wafers with different thickness are used for cell fabrication in order to eliminate material quality issues associated with thin film solar cells and to make the light trapping effect prominent. Front metal contacts are designed to form interdigitated lateral p-i-n junctions. Si solar cells with different intrinsic region width and variety of metal line length are fabricated in order to maximize the light penetration into the cell while keeping high carrier collection efficiency and fairly low series resistance. Tailoring the structure of grating and DBR optimizes the backside reflector structure and the cell efficiency. Specifically, for grating, different period and etch depth are used; and for DBR, SiO2/Si and Si3N4/Si with different number of quarter wave pairs are tried. The quantum efficiency of the integrated solar cell serves as a direct indicator of the best combination of grating and DBR parameters. Solar cell efficiency improvement due to the path length enhancement effect of our new back reflector should be much more pronounced in thin film solar cells. Key words: solar cell efficiency, photonic crystal, grating

4:00 PM EE6.7
Simultaneous confinement of light and microfluids by Bargg cladding waveguide. Yasha Yi, Shoji Akiyama, Xiaoman Duan and Lionel C. Kimerling; DMSE, MIT, Cambridge, Massachusetts.

Light guiding in low refractive index materials, such as microfluids and polymers, is very important for integrated biophotonics to realize lab-on-a-chip. A new planar waveguide based on CMOS technology is developed with light guiding in low index materials or air. We have fabricated an on-chip silicon-based Bragg cladding waveguide that has hollow core surrounded by a 1D photonic crystal cladding. The cladding consists of several dielectric bilayers; while each bilayer consists of a high index-contrast pair of Si and Si3N4. The new waveguide guides light based on the Bragg reflection principle, via reflecting light at any angle or polarization back into the core. This novel waveguide allows great flexibility in selecting guiding materials; and basically relieves the constraints of the traditional index guiding method. We recently demonstrated, the light and microfluids (fluorescence DNA and Protein solution) can be confined at extremely small volume simultaneously using our novel photonic waveguide; it opens a brand new window for integrated bio-photonics. In principle, a core of any low-index material can be realized with our novel structure, including air. The potential applications include biomaterials sensor, amplification of the sing molecule information, and integrated bio-photonics on chip.

4:15 PM EE6.8
Directional Growth of SiGe Nanowires on Insulating Films by Electric-Field-Assisted Metal-Induced Lateral Crystallization. Hiroshi Kanno, Atsushi Kenjo, Taizoh Sadoh and Masanobu Miyao; Department of Electronics, Kyushu University, Fukuoka, Fukuoka, Japan.

The low-temperature formation of high quality SiGe nanowires on insulating substrates has been expected to realize one-dimensional, quantum effect transistors with high speed operation. We have developed metal-induced lateral crystallization (MILC) of a-SiGe by using Ni as surfactant metal. This enabled needlelike SiGe crystals (width: ~0.05μm, length: ~10μm) on insulating films. To control their growth directions, present paper examined effects of electric fields on MILC. In the experiment, a-SiGe layers (thick: 50 nm, Ge fraction: 0~40%) were deposited on quartz substrate. Then, Ni films (thick: 15 nm) were deposited selectively on a-SiGe layers. This Ni films were used as the surfactant atom source and electrodes for bias voltage. The spacing between anodes and cathodes were 40-6000μm. Finally, the samples were annealed at 500°C with applying electric fields (0~4000 V/cm) between the electrodes. The crystal qualities were evaluated by using scanning electron microscopy and Raman spectroscopy. Under a low electric field (50 V/cm), random networks of needlelike SiGe crystals were formed. When the electric field was increased to 500 V/cm, needlelike SiGe crystals began to align. Under the extremely high electric fields (>2000 V/cm), all needlelike crystals propagated straight, where the growth direction was completely aligned to the electric field. These phenomena are attributed to the facts that kinetic energy of Ni atoms transferred from the high electric field (>1000 V/cm) exceeds that obtained by thermal energy at 500°C. These results clearly indicate that flow direction of surfactant atoms (Ni) during annealing can be controlled by external high electric fields. This advantage of laterally aligned SiGe nanowires on the insulating films should be used for one-dimensional SiGe quantum transistors.

4:30 PM EE6.9
Optical Properties of Long Semiconductor Nanowires Embedded in Photonic Crystal Fibers. Dong-Jin Won[1,2], Hui Fang[1,2], Adrian Amezcua-Correa[3], Chris. E. Finlayson[3], Neil Baril[4], Thomas J. Scheidemantel[4], Pier J.A. Sazio[3], Venkatraman Gopalan[1,2] and John V. Badding[4]; [1]Department of Materials Science and Engineering, The Pennsylvania State University, University Park, Pennsylvania; [2]Materials Research Institute, The Pennsylvania State University, University Park, Pennsylvania; [3]Optoelectronics Research Centre, University of Southampton, Highfield, Southampton, United Kingdom; [4]Department of Chemistry, The Pennsylvania State University, University Park, Pennsylvania.

We have developed a novel technique to incorporate highly ordered arrays of the longest semiconductor micro- and nanowires (up to ~30 cm long) demonstrated to date, by filling the holes of a Photonic Crystal Fiber (PCF) by high pressure chemical vapour deposition (HPCVD) technique. Semiconductor filled Microstructured Optical Fibers (MOFs) potentially open up the new area of all-fiber optoelectronics, where light generation, modulation, and detection are all integrated seamlessly within a fiber. In this talk, we will discuss silicon and germanium filled PCF silica fibers. In a silicon-filled capillary fiber, the 1.55 μm continuous wave was successfully guided into the Si-core. Cutback measurement showed a propagation loss of 2.8 dB/cm, which is superior to the lowest loss of 9 dB/cm for poly-silicon waveguides reported in literature. Similarly, optical guiding of 2.5 μm wavelength and 130 fs laser pulses through Ge-filled

capillary fibers exhibited a propagation loss of 1.6-2.8 dB/cm. Fabry-Perot etalon studies of light through the fiber were used to characterize both linear and nonlinear optical properties in Si-filled fibers. A Field-Effect Transistor based on Si-filled PCF is also demonstrated.

4:45 PM EE6.10
Photocurrent Spectroscopy on Single Heterostructure Nanowires. Johanna Tragardh[1], Ann I. Persson[1], Dan Hessman[1], H. Petterson[2], L. Landin[2] and L. Samuelsson[1]; [1]Solid State Physics, Lund University, Lund, Sweden; [2]Laboratory of Mathematics, Physics and Electrical Engineering, Halmstad University, Halmstad, Sweden.

Nanowires (NWs) have for the past years attracted considerable attention due to the interesting fundamental properties present in such low-dimensional systems and the exciting prospects for utilizing these materials in future nanotechnology-enabled electronic and photonic applications. It has recently been shown that it is possible to form heterostructures in NWs facilitating 1-D electronics e.g. resonant tunneling diodes [1] and single-electron transistors [2]. In this work we report on spectrally resolved photocurrent (PC) measurements on single self-assembled InAs/InAs$_x$P$_{1-x}$ nanowire heterostructures. The wires were grown vertically with chemical beam epitaxy (CBE) using gold seed particles to locally increase the growth rate below the particle, i. e. at the nanowire-particle interface. After growth, the wires were removed from the substrate and deposited on a SiO2 surface. Ohmic contacts to the InAs ends of the wire were prepared using e-beam lithography. The dark current in the wire is strongly reduced by the heterostructure band offset. The PC measurements were made at 4K, and at such low temperatures the dark current was orders of magnitude less than the PC, which was about 1nA. The wires used for PC measurements were about 80nm thick wires with a 1μm long InAsP central segment. The phosphor content of the InAsP segments were estimated from energy dispersive spectroscopy measurements made in TEM. The PC was measured using a Fourier transform spectrometer. The spectra revealed an interband excitation process in the InAsP segment with threshold energies in good agreement with the expected bandgap as based on the composition estimates. Furthermore, a strong polarization dependence was observed, with an order of magnitude larger current for light polarized along the wire compared to light polarized perpendicular to the wire. These spectrally resolved PC measurements thus confirm previously reported polarization dependence in PC measurements on nanowires [3]. We believe that these wires are promising candidates for infrared polarization sensitive photodetectors. The good contacts formed to InAs is for these wires combined with a low dark current level, that can be tuned by changing the composition of the InAsP segment of the wire. [1] M. T. Björk, et al. *Appl.Phys.Lett.* 81, 4458 (2002). [2] C. Thelander, et al. *Appl.Phys.Lett.* 83, 2052 (2003). [3] J. Wang, et al. *Science* 293, 1455 (2001)

TURNBULL LECTURER AWARD TALK PRESENTATION

Tuesday Evening, November 29, 2005
5:05 PM
Grand Ballroom (Sheraton)

Isotopically Controlled Semiconductors. Eugene E. Haller, Materials Science and Engineering Department, University of California-Berkeley, Berkeley, California.

"For pioneering achievements and leadership in establishing the field of isotopically engineered semiconductors, for outstanding contributions to materials growth, doping, and diffusion, and for excellence in lecturing, writing, and fostering international collaborations"

Scientific interest, increased availability, and technological promise of highly enriched isotopes have led to a sharp rise in the number of experimental and theoretical studies with isotopically controlled semiconductor crystals. This talk will review results obtained with isotopically controlled semiconductor bulk and thin-film heterostructures. Isotopic composition affects several properties such as phonon energies, bandstructure, and lattice constant in subtle, but, for their physical understanding, significant ways. Large isotope-related effects are observed for thermal conductivity in local vibrational modes of impurities and after neutron transmutation doping (NTD). Spectacularly sharp photoluminescence lines have been observed in ultrapure, isotopically enriched silicon crystals. Isotope multilayer structures are especially well suited for simultaneous self- and dopant-diffusion studies. The absence of any chemical, mechanical, or electrical driving forces makes possible the study of an ideal random-walk problem. Last, but not least, isotopically controlled semiconductors may find applications in quantum computing, nanoscience, and spintronics.

SESSION EE7: Poster Session: Progress in Semiconductor Materials V - Dielectrics, Silicon-, Carbon-, and Nano-Materials
Tuesday Evening, November 29, 2005
8:00 PM
Exhibition Hall D (Hynes)

EE7.1
Thermal desorption studies of Hydrogen trapping in HfO2/Si structures. Vaishali Ukirde, Ezekiel Walker, Changduk Lim and Mohamed El Bouanani; Laboratory for Electronic Materials and Devices, Department of Material Science & Engineering, University of North Texas, Denton, Texas.

Hydrogen plays major role in semiconductor technology, due to its pervasiveness in a variety of processes such as deposition and post annealing of electronic structures. Therefore, it has become increasingly important to better understand the properties and behavior like trapping and release of hydrogen in semiconductor in order to improve electronic performance of the Metal-Oxide-Semiconductor (MOS) structures. Hydrogen is known to have most ambivalent (both beneficial and harmful effects) behavior in MOS devices. Trap transformations under annealing treatments in hydrogen ambient is known to be highly efficient in improving the device characteristics by passivating defects at the SiO2/Si interface. Comparable behavior is observed in the high-k dielectrics based MOS structures. Despite wealth of electrical knowledge there is little direct information about the actual location and concentration of hydrogen and effects under hydrogen annealing in high-k dielectrics based MOS devices. The effect of processing ambient and annealing time on the hydrogen trapping and release will be reported. Elastic Recoil Detection Analysis was used to quantify the trapped hydrogen in the bulk of HfO2/Si structures that were subjected to oxygen pre-processing followed by Forming Gas post anneals. Thermal desorption study of hydrogen from HfO2/Si structures and possible trapping and release mechanisms will be discussed.

EE7.2
The Effect of Oxide Bulk Defect on NBTI. MiJin Kim, YoungJoo Song and BongKi Mheen; Electronics and Telecommunications Research Institute, Daejeon, South Korea.

With aggressive scaling down, the reliability of the oxide films becomes the important issue. As oxide electric field approaches 10MV/cm and gate oxide thickness under 20A, rapid Idsat decrease and Vth shift under negative bias temperature stress (NBTS) are the major reliability issue. Widely accepted model for Negative Bias Temperature Instability (NBTI) is Reaction-Diffusion (R-D) model originally proposed by Joppson and Svensson, because the R-D model can only explain the time dependence of device parameters in NBTI. The R-D model attributes the creation of positive charges to the depassivation of Si-H bond in the Si-gate dielectric interface and the rate controlling step to diffusion of desorbed hydrogen away from the interface. But R-D model has limitations on explaining the saturation effect of device parameter in long term NBTS and variation of time dependence factor(n) lied in the range 0.2$\sim$0.3. Recently dispersive hydrogen diffusion model and stretched exponential model were adapted to governing the long term kinetic and AC behavior of NBTI. But only a few works have studied on the effect of oxide bulk defects on NBTI, especially on kinetic influence (time dependence factor (n) and a measure of dispersion (?)). In this work, PMOSFETs with three gate oxide material, SiO2, SiON with low and high nitrogen concentration, were examined at various time and temperature. The activation energies of NBTI have similar value regardless of gate oxide materials. Time dependence factor (n) of SiO2 gate oxide material was 1/4 similar with previous reported data. But for SiON, NBTI became worse and fast. Time dependence factors (n) of SiON with low and high N concentration gate oxide material were about 1/2.4. When oxide defects were produced by F.N. prior to NBTS, the time dependence factor (n) of SiON with high N concentration increased to 1/2.4. Bulk oxide traps make NBTI faster. If hydrogen diffusing away from the interface was captured by the bulk defect for passivation of bulk defect, reduced hydrogen concentration in bulk can accelerate the rate of NBTI. Actually, the oxide bulk traps measured by 1/f noise indicated that increased oxide bulk trap by F.N. were annealed out by successive NBTS.

EE7.3
Diffractive MEMS in Spectroscopy. Mouli Ramani, Polychromix,

Wilmington, Massachusetts.

Conventional methods of performing chemical identification, namely measuring the entire spectrum of transmitted light across some pre-selected range of wavelengths, and then analyzing the collected light to identify characteristic absorption lines of target chemicals, can be improved through the use of recent technical developments. One goal of modern instrumentation is to make chemical-sensing measurements more efficient with respect to speed, the use of available light energy from the source, and cost, for example by using a single detector rather than an array. The Micro-Electro-Mechanical Systems (MEMS) technology, currently used in telecommunications now can be applied to spectroscopy to create various patterns of "off-on" filters, passing some bands, blocking others. A technique known as Digital Transform Spectroscopy allows a complete spectrum to be collected with a single detector using a time sequence of filter patterns. An important application is the analysis of mixtures of compounds, known as "chemometrics." Chemometric analysis extracts a weighted sum of light absorbances at different wavelengths to perform the separation. This paper reviews the properties of diffractive MEMS devices and examines their applications in chemical spectroscopy.

EE7.4
Tune the optical band gap and refractive index : the mixed anions (F,O,S) systems. Alain Demourgues, Damien Pauwels, Nicolas Viadere, Nicolas Penin, Laetitia Sronek, Stephane Jobic and Alain Tressaud; ICMCB-CNRS, Pessac Cedex, France.

Design of new inorganic compounds with flexible band gap in the UV-Vis-NIR domain has attracted considerable attention for the development of UV-IR shielding, colored pigments, X-chromism and solar applications in general. Solar interactions with pigments (UV-Vis-NIR) lead to relevant phenomena such as absorption and scattering allowing to define complex indexes $n(\lambda) + ik(\lambda)$. Actually, the optical band gap related to the electronic structures as well as the refractive index function of the network polarizability can be tailored by changing the nature and the number of anions into the vicinity of cations. Hydrothermal routes have been developed in order to prepare new divided Ti(IV), Sn(IV) or Ce(IV)-based oxyfluorinated compounds. In this series the optical absorptions appear at the UV-Vis frontier or Vis-NIR region in the case of Sn(IV) and the refractive index is always smaller than homologous oxides. The chemical bonding, the hybridization and the density of the network play key roles in the variation of the optical band gap and the refractive index. On the other hand new rare earth-based fluorosulfides and oxyfluorosulfides have been prepared by solid state routes and depending on the compositions, UV absorbers, yellow and red pigments have been characterized. In this series of mixed anions systems, chemical compositions, structural features and networks have been correlated to the optical band gap and the refractive index, i.e the complex index of materials. Several examples will be given in order to illustrate the potentialities of these new inorganic compounds having adjusted optical band gaps from UV to Vis and IR domains as well as various values for the refractive index in these regions.
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EE7.5
Thin multiwall carbon nanotube field emitters with microchannel plate for high current emission.
Raghunandan Seelaboyina, Jun Huang and Wong Bong Choi; Mechanical & Materials Engineering, Florida International University, Miami, Florida.

Electron beam source based on carbon nanotube field emitters with microchannel plate (MCP) are suitable for plasma and high power microwave applications. In this work, field emission measurements were conducted on thin multiwall carbon nanotubes with a MCP, in which each channel acts as an electron multiplier, placed between the anode and cathode. An increase in brightness, uniformity of luminescent light and relatively high current density with low applied field was observed with MCP. Aligned thin multiwall carbon nanotubes were synthesized on Nb/SiO2/Si substrate by using Mo/Fe particles supported by aluminum oxide (Al2O3) nano particles as catalyst by chemical vapor deposition. High density carbon nanotubes (CNTs) were synthesized by varying the amount of Al2O3 leading to their vertical alignment. The inner and outer diameters of the CNTs determined from the radial breathing mode (RBM) peaks of Raman spectra were in the range of 2.5-5 and 7-15 nm, respectively. These diameters were in good agreement with the transmission electron microscopy measurements. The turn-on voltage was 0.5-1V/?m with a field enhancement factor of 9,296. Emission current from the CNTs in DC mode was stable, with an average fluctuation of less than 2% for over 2.5 hours. Space charge effect on field emission will be analyzed using the charged particle optics (CPO) software in order to get the maximum emission current.

EE7.6
Dielectric Properties of Ultrananocrystalline Diamond Thin Films. Chao Liu[1], Xingcheng Xiao[1], John A. Carlisle[1,2] and Orlando Auciello[1,2]; [1]Material Science Division, Argonne National Laboratory, Argonne, Illinois; [2]Center for Nanoscale Materials, Argonne National Laboratory, Argonne, Illinois.

Ultrananocrystalline diamond (UNCD) thin film is potentially a good candidate for low-trap dielectric material used in RF MEMS capacitive switches. It has an extremely smooth surface and exceptional mechanical properties including high hardness ($\sim$90 GPa) and fracture strength (5 GPa). Its intrinsically hydrophobic surface gives rise to low adhesion energies between the UNCD thin film and the moving membrane during the operation of the switch. More importantly, its dielectric conductivity and dissipation characteristics can be 'tuned' in a wide range. Compared with typical charging dielectrics (for instance, SiNx), UNCD thin films can provide faster charge releasing, which prevents functional failures of the MEMS switches, such as actuation voltage drift and unintentional release of the device, due to the charge build-up in the dielectric material. In this work, the dielectric properties of hydrogen-incorporated UNCD thin films are studied. UNCD thin films are synthesized in argon-rich plasmas with various percentages of hydrogen additions in the gas feedstock. Previous to the UNCD deposition, a layer of tungsten film (bottom electrode) is sputtered on a silicon wafer with a $1\mu m$ thick thermally grown silicon dioxide layer. The top electrodes that are patterned with a shadow mask are subsequently deposited onto the UNCD thin films. Impedance and DC measurements are carried out on a probe station with two probes connected to the top and bottom electrodes respectively. It has been found that, with increasing the addition of hydrogen in the gas mixture (0$\sim$10%) during the UNCD deposition, the resistivity of the UNCD film can be tuned in the range of 10^4 to 10^8 $\Omega\cdot$cm. The breakdown electric fields for those films are also a strong function of the percentage of hydrogen in the gas mixture. It is believed that the hydrogen atoms incorporated into the UNCD thin films saturate the carbon dangling bonds in the UNCD grain boundaries, which significantly impacts the dielectric properties of the UNCD thin films. I-V measurements of the UNCD capacitors show a non-linear behavior. The dielectric constant and the dissipation factor of the UNCD thin films are measured using an impedance analyzer and a frequency range up to several MHz. C-V measurements are also performed with DC bias applied across the UNCD thin films. It is observed that the capacitance can be tuned by the applied DC bias at a given frequency. The UNCD films studied here exhibit relatively high loss tangent and leakage current, the later being a required condition for dielectric layers used in capacitive RF MEMS switches to avoid undesirable charging effects. The charge injection, retention, movement, and releasing behaviors of the UNCD films are discussed. This work is supported by the US Department of Energy, BES-Materials Sciences, under Contract W-13-109-ENG-38.

EE7.7
Electron emission mechanism of diamond characterized by combined XPS/UPS/FES. Hisato Yamaguchi[1], Bradford B. Pate[2], M. Kudo[3] and Ken Okano[1]; [1]Department of Physics, International Christian University, Mitaka, Tokyo, Japan; [2]Department of Physics, Washington State University, Pullman, Washington; [3]JEOL ltd., Musashino, Tokyo, Japan.

An attempt was made to clarify the emission mechanism on diamond using combined XPS/UPS/FES. Although there have been number of studies on individual spectroscopy using XPS, UPS, and FES, an integrated study was rarely reported [1, 2]. Diamond has gained much attention as a cold cathode [3], however, its emission mechanism is not yet clarified. The advantage of the combined spectroscopy developed for this study is that it enables a spectroscopy effective for clarification of electron emission mechanism on diamond. The field emission characteristics of diamond can be strongly affected by surface modification [4], such as terminated atoms and electron affinity. Correlation between surface termination obtained by XPS, electron affinity estimated by UPS, and energy distribution of field emitted electron by FES, thus, would provide distinguished information on the origin of emitted electrons. The system in which we have developed for this study consists of ultraviolet source (Thermo Electron Corp., Model 232) built in an X-ray photoelectron spectrometer (JEOL-9010MX). UPS measurement was performed using Helium gas discharge illumination at the energy of 21.2 eV (He I) with a 100mm radius hemispherical analyzer. Mgka (1253.6 eV) operated at 100W (10kV, 10mA) is used as an x-ray source in a vacuum chamber with a base pressure of 5 x 10-10 Torr. The sample could be negatively biased up to 4kV relative to the mesh grid for field emission measurements.

The system enables to obtain two-dimensional distribution for all three spectroscopy by means of a movable sample stage together with an aperture located at the entrance of input lens of the analyzer. The combined spectroscopy of UPS/FES was conducted on CVD diamond. The sample was first biased up to sufficient voltage for field emission. The surface is, then, simultaneously illuminated with He I excitation (hv=21.2 eV) for photoemission. When the He I illumination is turned off, emission is no longer observed at kinetic energies (KE) above 340.0 eV, while the emission below 340.0 eV remains within a slight change. This clearly indicates that the energy distribution consists of both field-emitted electrons and photo-excited electrons. Derived from calculation using obtained high energy cut-off of the spectra, the field emitted electrons originate from the band gap of the diamond, approximately 1 eV above the VBM. Further investigation on correlation between surface termination by XPS, and obtained UPS/FES could effectively conducted by moving sample holder in a matrix form with an aperture for the XPS/UPS/FES mapping. References: [1] C. Bandis, and B. B. Pate, Appl. Phys. Lett. 69, 366 (1996). [2] R. Schlesser, M. T. McClure, B. L. McCarson, and Z. Sitar, J. Appl. Phys. 82, 5763 (1997). [3] K. Okano, S. Koizumi, S. R. P. Silva, and G. A. J .Amaratunga, Nature (London) 381, 140 (1996). [4] H. Yamaguchi, T. Mine, Y. Suzuki, K. Okano, T. Yamada, and A. Sawabe, J. Vac. Sci. Technol. B 21, 1730 (2003).

EE7.8

Prediction of Young's Modulus of Low Dielectric Constant Materials by Atomistic Molecular Dynamics Simulation.
Hyuk Soon Choi[1], Taebum Lee[2], Hyosug Lee[1], Jongeseob Kim[1], Kiha Hong[1], Kwang Hee Kim[1], Jaikwang Shin[1], Hyun Jin Shin[3], Hyun Dam Jung[3] and Seung-Hoon Choi[2]; [1]CSE Center, Samsung Advanced Institute of Technology, Yongin-Si, Gyonggi-Do, South Korea; [2]Insilicotech Co. Ltd.,, Seongnam-Si, Gyeonggi-Do, South Korea; [3]Material Laboratory, Samsung Advanced Institute of Technology, Yongin-Si, Gyeonggi-Do, South Korea.

The interests of low dielectric materials to reduce capacitance in multilevel metal interconnects of integrated circuits are well known in the semiconductor industry. Integration centers on the low-k film's mechanical properties. Improved hardness and modulus are desirable because, when building a multilayered stack and doing sequential processing, films go through chemical mechanical planarization (CMP). In this proceeding, we investigated the mechanical strength (Young's modulus) of the typical low k candidates materials, and reports the fundamental understanding on Young's modulus effected by various aspects, such as, structures of precursors, density, and porosity. Using atomistic molecular dynamics simulation with experimental measurements, the Young's modulus of films of amorphous silicon oxide in which 25% of Si-O-Si chains were replaced by Si-(CH3 H3C)-Si, Si-CH2-Si, Si-(CH2) 2-Si, Si-(CH2) 3-Si, Si-(CH2)4-Si, Si-(CH2)6-Si, are determined and analyzed. The predicted trends of Young's moduli of films formed by above precursors are in good consistent with those observed from experiments. The Young's moduli of materials are largely dependent on the densities of materials. Young's modulus of material decreases as the density of the material increases. The chemical properties, chain length, and connectivity of material take effects on the Young's modulus of material. Given the same densities of material the smaller number of cavities per unit volume the material has, the lower Young's modulus it shows. Based on the results, the method for the prediction of mechanical properties of materials by the conjunction of basic experimental measurements and atomistic simulation will be discussed.

EE7.9

The effect of nitrogen addition on the morphology and quality of boron doped diamond films.
Koji Iwasaki[1], Mikka Nishitani-Gamo[1], Hidenori Gamo[2], Kiyoharu Nakagawa[3] and Toshihiro Ando[3]; [1]Department of Applied Chemistry and Sensor Photonics Research Center, Toyo University, Kawagoe, Saitama, Japan; [2]Technical Research Institute, Toppan Printing Co. Ltd, Sugito, Saitama, Japan; [3]Advanced Materials Laboratory, National Institute for Materials Science (NIMS), Tsukuba, Ibaraki, Japan.

We investigated the effect of simultaneous diborane and nitrogen addition on the chemical vapor deposited diamond growth. The morphology and quality of the doped diamonds were studied by Scanning Electron Microscopy (SEM) and Micro Raman Spectroscopy. The growth conditions are shown in table 1. The doped diamonds were grown on Si substrates by the microwave plasma-assisted chemical vapor deposition (MPCVD) method. For boron doping, diborane (B2H6) gas was introduced in the range from 0 to 10 ppm in the gas phase. Nitrogen was introduced in the range from 0.0 to 2.0 %, as well. We observed the SEM images of the isolated diamond crystals deposited both with 0.8% N2 addition and a different amount of B2H6 addition of 10 ppm, 5 ppm, and 2 ppm in the gas phase, respectively. In the case of the lower B2H6 concentration (2 ppm), the isolated diamond showed a sphere like morphology. Contrary to this, at the B2H6 addition of 10ppm in the gas phase, the isolated diamond crystals were grown with cubo-octahedral shapes. It was reported that the added N2 in the gas phase gave a sphere-like crystal. Nitrogen was incorporated into the crystal and degraded the crystallinity. The effect of nitrogen addition decreased with increase of the B2H6 concentration in gas phase.

EE7.10

On axis confined Cell structure to Reduce Writing Current for High Density PRAM.
Ryoo Kyung-Chang, Y. N. Hwang, Y. J. Song, H. S. Jeong and K. N. Kim; Advanced Technology Development Team, Samsung Electronics Co., Ltd., Seoul, Kyunggi-Do , South Korea.

To reduce the writing current required for high density, high-speed and low-power Phase-change Random Access Memory (PRAM) is investigated. Especially, we proposed advanced on axis confined structure which can be reduced writing current controlled by new cell fabrication method. We also evaluated based on 64Mb PRAM with 0.12 um-CMOS technologies. With the fabrication of this structure as a result, feasibility for developing high-density PRAM in the future is presented.

EE7.11

Heterojunction, Vacuum-Glass Field Effect Transistors.
Michael W. Geis[1], Sandra J. Deneault[1], Keith E. Krohn[1], Michael F. Marchant[1], Theodore M. Lyszczarz[1] and David L. Cooke[2]; [1]Submicrometer Technology, MIT Lincoln Laboratory, Lexington, Massachusetts; [2]Space Vehicle Directorate, U.S. Air Force Research Lab, Bedford, Massachusetts.

Electrons can float in vacuum on the surface of negative electron affinity (NEA) materials much like electrons can be restricted to the interface between two semiconductors in heterojunction devices. These electrons are bound by electrostatic attraction to the NEA material, but are quantum mechanically forbidden to enter the bulk. Liquid He, where electrons are stable on its surface for hours,[1] and Ni, where the electrons are stable for ~100 fs,[2] are examples of NEA materials. CsCl (Ref. 3) and diamond[4] are examples of NEA insulators, but little has been done to characterize their surface electrical properties. This presentation reports on a field effect transistor where the electron channel consists of the interface between vacuum and a NEA Cs-doped glass; an electrode on the back of the glass substrate is used as the gate. The device has a transconductance of 4×10^{-10} S cm^{-1}. With drain-source electrodes, on the glass, spaced 10 μm apart, a glass insulator thickness of 2 μm and a drain-source voltage of 230 V, the calculated electron mobility is 6×10^{-5} cm^2 V^{-1} s^{-1}. This should be compared with $\sim 10^7$ cm^2 V^{-1} s^{-1}, the mobility of electrons on liquid He.[1] The electrons on glass are lightly bound to the glass surface and an electric field as low as 10 V cm^{-1} will pull them into vacuum. At higher vacuum electric fields the electrons can be pulled into vacuum with current densities of ~1 A cm^{-2}. The W drain-source electrodes have a work function of several electron volts, while the effective work function of the surface electron gas is ~ 0.4 eV. Tunneling of electrons from the electrodes onto the glass surface is facilitated by a unique electrode geometry. The electrodes are a laminate of 50 nm of Al and 100 nm of W. During processing the Al is chemically wet etched undercutting the W layer. This undercut structure is crucial both for FET devices and for electron emission as a cathode. The presentation will discuss fabrication and electrical characterization of both the vacuum FET and the cathode. A theoretical model explaining the function of the undercut drain-source W electrodes and possible applications of these devices will be given. 1. M. W. Cole, Rev. Mod. Phys. 46, 451 (1974). 2. X. Y. Zhu, Annu. Rev. of Phys. Chem. 52, 221 (2002). 3. G. Yoshikawa, M. Kiguchi, K. Ueno, A. Koma, and K. Saiki, Surf. Sci., 544, 220 (2003). 4. M. W. Geis, J. A. Gregory, B. B. Pate, IEEE Trans. Electron Devices 38, 619 (1991). This work was sponsored by the Air Force Office of Scientific Research under Air Force Contract FA8721-05-C-0002. Opinion, interpretations, conclusions, and recommendations are those of the authors and are not necessarily endorsed by the United States Government.

EE7.12

Materials optimization for high speed silicon optical modulators.
Ling Liao[1], Dean Samara-Rubio[1], Doron Rubin[2], Michael Morse[1], Dexter Hodge[3], Ulrich Keil[4], Thorkild Franck[4] and Mario Paniccia[1]; [1]Intel Corp., Santa Clara, California; [2]Intel Corp., Jerusalem, Israel; [3]North Carolina State University, Raleigh, North Carolina; [4]Intel Corp., Copenhagen, Denmark.

We recently demonstrated a silicon-based optical modulator with an intrinsic bandwidth of 10 GHz and data transmission up to 10 Gbps. Here we discuss the materials challenges associated with achieving such high speed performance. The modulator is based on a MOS-capacitor design where a gate dielectric is sandwiched between two layers of silicon. This design necessitates the deposition or growth

of silicon on top of the gate dielectric. Devices based on both polycrystalline silicon (poly-Si) and epitaxial silicon, grown using the epitaxial lateral overgrowth (ELO) technique, have been fabricated and characterized. We discuss in detail how the different materials affect dopant activation, device transmission loss, and device speed. Experimental data suggests that the optical transmission of poly-Si is governed by the physical concentration, not the activated carrier concentration, of dopants. As a result, devices with the same doping level and therefore the same transmission loss could have significantly different device speeds if dopant activation, which determines material resistance, is different. For example, two modulators, one with poly-Si and the other with ELO-Si, while having the same transmission loss of ~18 dB/cm, have significantly different bandwidth performance. Because the poly-Si has less than 10% dopant activation, device speed is limited to ~2.5 GHz. The ELO-Si, on the other hand, has nearly 100% activation and therefore enables much improved device speed of ~10 GHz. Detailed materials and device data will be presented; optical modeling results will also be shown for comparison.

EE7.13
Abstract Withdrawn

EE7.14
Si Thin Film Growth by Pulsed Plasma CVD under Near-Atmospheric Ppressure. Hirotatsu Kitabatake[1], Maki Suemitsu[1], Tsuyoshi Uehara[2], Setsuo Nakajima[2] and Yasutake Toyoshima[3]; [1]Center for Interdisciplinary Research, Tohoku University, Sendai, Miyagi, Japan; [2]Sekisui Chemicals Co. Ltd., Osaka, Osaka, Japan; [3]Energy Technology Research Institute, National Institute of Advanced Industrial Science and Technology, Tsukuba, Ibaraki, Japan.

Plasma-enhanced chemical vapor deposition (PECVD) has been widely investigated because of its ability to produce amorphous and microcrystalline Si thin films at low temperatures, which is suitable for making thin-film solar cells or thin-film transistors. While conventional PECVDs are mostly operated at reduced pressures, the one operated at near-atmospheric pressures (NAP-PECVD) has evoked recent attention in that it has a potential advantage in increasing the growth rate by utilizing its much higher density of reactive species generated in the discharge plasma. Possible cost reduction of the reactor is also advantageous since the NAP-PECVD can go without the evacuating instruments. We have developed a pulsed-electric-field based NAP-PECVD system, in which no restrictions are imposed on the kinds of the gas materials for stable discharge. This is a clear contrast to the conventional atmospheric operations where high dilution by noble gases, typically helium, is inevitable. One of the most prominent feature is obtained in the Si film growth on the glass substrates at 180°C with a gas mixture of monosilane (1.5 sccm) and hydrogen (499-1500 sccm) under NAP (300-700 Torr) conditions. Raman scattering and X-ray diffraction indicate the films are mainly polycrystalline, with the typical grain size of ~10 nm. Observation by cross-sectional transmission electron microscopy (X-TEM) revealed that no incubation layer is formed at the polycrystalline-film/glass-substrate interface, despite the growth rate as high as 1 nm/s. We ascribe this feature to be originated from the combination of extremely high dilution of monosilane by hydrogen, in which condition the nucleation (and thus the elimination of incubation layer) is favored, and of very high density of reactive species for the film growth, which is inherent in NAP systems. Under similar growth conditions, we have employed p-type Si (001) substrates. The Raman spectra of the grown layer showed a dominant crystalline peak at 520cm-1, with a trace of amorphous-related broadening around 480 cm-1, indicating that the layer is mainly in the crystalline phase. The electron-beam diffraction taken at the X-TEM observation indicates that the grown layer is mostly consisted of a single-crystalline phase whose lattice is aligned to the substrate. From this observation, we judge this growth is highly likely to be epitaxial, if not perfect. Although there are much left to be investigated, these features described here are enough to show the high potential of our pulsed-discharge based NAP-PECVD for Si growth.

EE7.15
Microstructural Characterization of 3C-SiC Grown on Undulant-Si (001) Substrates. Kotaro Kuroda, Suguru Kodama, Hiroyuki Miyazaki and Katsuhiro Sasaki; Department of Quantum Engineering, Nagoya University, Nagoya, Japan.

A new technique to reduce planar defects in 3C-SiC that involved growing 3C-SiC on "undulant-Si" substrates with slopes oriented in the [110]- and [-1-10]-direction was developed by Nagasawa et al. in 2000. Microstructural characterization of the 3C-SiC single crystals from HOYA has been carried out by transmission electron microscopy. Specimens for TEM cross-sectional observation have been fabricated using a focused ion beam technique. Many planar defects are observed near the 3C-SiC/Si(001) interface, and those are identified to be stacking faults and inversion domain boundaries. The density of stacking faults is observed to decrease as the SiC thickness increases. Reduction of stacking faults seems to be affected by the effect of undulant-Si.

EE7.16
Improved Interface Properties of Polyoxide on n-type 4H-SiC by Wet Oxidation and Ar Annealing. P. Li, A. Rodriguez, Y.v. Prakash, R. Shankar, J. E. Ayers and F. C. Jain; Electrical & Computer Engineering, University of Connecticut, Storrs, Connecticut.

Besides native oxide, a variety of materials have been studied as insulators in SiC-based MIS devices. Polyoxide, from oxidation of polysilicon, has the potential benefits of faster oxidation rate, uniform oxide formation and less carbon involvement. In this paper we present the fabrication of SiC-based polyoxide MOS capacitors on 4H-SiC and the reduction of interface state densities with wet oxidation and Ar annealing. The n-type 4H-SiC epitaxial wafers used in this study were obtained from Sterling Semiconductor. Polysilicon was deposited by chemical vapor deposition using silane in an Emcore Turbodisc system at 720°C and 100 torr. Dry and wet oxidation of the polysilicon were performed at 1100°C for 20 to 30 minutes. The short oxidation time for the polysilicon (compared to the case of native oxide) was expected to minimize CO generation at the interface. Typical polyoxide layers were 50 nm thick. Some samples were annealed at 1100°C in Ar for 60 minutes after oxidation. Combined high and low frequency capacitance-voltage measurements showed a relatively low interface state density (Dit) of $2.6\text{x}10^{11}$ $cm^{-2}eV^{-1}$ at 0.5 eV below the conduction band for polyoxide samples grown by wet oxidation and annealed in Ar. The polyoxide samples grown by wet oxidation without an anneal had a higher Dit of $1.2\text{x}10^{12}$ $cm^{-2}eV^{-1}$ and the polyoxide samples grown by dry oxidation had the highest Dit of $1.8\text{x}10^{12}$ $cm^{-2}eV^{-1}$ at 0.5 eV below the conduction band. The drop of Dit after Ar annealing could result from the stress relaxation at the polyoxide/4H-SiC interface induced by high temperature treatment. Ar annealing did not show a significant impact on the interface properties of native oxide grown on 4H-SiC. It is possible in that case that the stress relaxation is already completed during the lengthy oxidation process.

EE7.17
Low Leakage Current Transport and High Breakdown Strength of HfO2/SiC MIS Device Structures.
Shiva S. Hullavarad, E. B. Jones, R. D. Vispute and T. Venkatesan; Center for Superconductivity Research, University of Maryland, College Park, Maryland.

Robust high-temperature passivation and gate dielectric materials are required for SiC analog power control devices and embedded digital fault protection circuitry to implement future military and commercial electric drive applications. These future applications will require dielectric materials that are stable at temperatures upto 350C under operating fields of atleast 1MV/cm. Thermally grown and deposited-reoxydized SiO2 gate dielectrics as thin as 1.5 nm on SiC are under development but have not yet been demonstrated to provide stable and reliable MOSFET operation even at a temperature of 300o C and a gate field of 1MV/cm. Therefore, other insulators, especially, those with higher dielectric constants resulting in lower field in the insulator are preferred. In this work we have grown high quality HfO2 with a dielectric constant about 25 on SiC. HfO2 films were deposited by Pulsed Laser Deposition technique on p-SiC substrates. The substrates were cleaned by standard technique to remove any native oxides. The oxygen gas partial pressure and growth temperatures have been optimized to get the good electrical (low leakage) properties on HfO2/SiC MIS device. A suitable metal contact with low contact resistance on HfO2 has been identified in this work. I-V and C-V characteristics are measured on standard Kiethley/HP LCR Analyzer set up. The low leakage current density of 40 nA/cm2 at room temperature was recorded. The activation energy has been estimated to be around 0.64 eV and the dielectric constant evaluated from C-V measurements is in close agreement with the theoretical values. The temperature dependence I-V characteristics of HfO2/SiC based MIS devices indicate that the electrical transport is dominated by the barrier height associated with bandgap off set between HfO2 and SiC.

EE7.18
High Temperature Capping Layers of TaC, AlN & BN for Development of SiC Based Power Devices. Shiva S. Hullavarad[1], Frederick Housel[1], R. D. Vispute[1], S. Dhar[1], T. Venkatesan[1], K. A. Jones[2], T. S. Zheleva[2] and M. A. Derenge[2]; [1]Center for Superconductivity Research, University of Maryland, College Park, Maryland; [2]Sensors and Electron Devices Directorate, Army Research Laboratory, Adelphi, Maryland.

Silicon Carbide (SiC) is a wide band-gap semiconductor suitable for high temperature, high power devices with potential applications in hybrid electric vehicles capable of operating in harsh environments.

The technique of selective area growth (SAG) or ion implantation are widely used to achieve the required type and concentration of carriers. The dopant activation by annealing requires annealing at high temperatures of 1600 C for n type dopants and 1700 C for p-type dopants. However, the annealing at these temperatures leaves the surface of SiC devoid of Si and traces of carbon. This effect also introduces non-stoichiometric defects that may hamper the device operation. We have developed a host of capping layers to address the needs of annealing to activate the dopants while retaining the surface smoothness and most importantly the stoichiometry of the surface. We have employed the Pulsed Laser Deposition (PLD) technique with highly optimized process parameters to grow high quality capping layers of TaC, WC, AlN, BN, and AlN/BN. In case of lower temperature (800C) grown films, surface morphology shows agglomeration of effects during annealing above 1400C and partial decomposition at 1700C. For retaining the smooth quality of caps during high temperature annealing, we have grown capping films close to 1/3 of the melting temperature (1100-1200C). The epitaxial growth of the PLD deposited films and the implanted SiC device structures are characterized using X-ray diffraction (XRD), Rutherford Back Scattering (RBS) Spectroscopy, Scanning Electron Microscopy (SEM), and Transmission Electron Microscopy (TEM). The high temperature grown TaC films on SiC show single phase (111), excellent crystalline quality with XRD rocking curve widths of 0.2-0.4o. These analysis techniques are used to study the morphology and crystalline quality of the high temperature capping films and SiC substrates before and after the annealing process. A review of capping layers of AlN, BN and AlN/BN, TaC and WC will be presented. Additionally, use of the stable caps for masking in selective area growth of SiC will be discussed.

EE7.19
Abstract Withdrawn

EE7.20
Implantation and Activation of High Concentrations of Boron and Phosphorus in Germanium. Yong Seok Suh[1], M. S. Carroll[2], R. A. Levy[1], G. Bisognin[3], D. De Salvador[3] and M. A. Sahiner[4]; [1]Physics Department, New Jersey Institute of Technology, Newark, New Jersey; [2]Sandia National Laboratories, Albuquerque, New Mexico; [3]MATIS-INFM and Dipartimento di Fisica, Universita di Padova, Padova, Italy; [4]Evans East, East Windsor, New Jersey.

There is renewed interest in the development of Ge high speed & optoelectronic devices. Implantation and activation are critical process steps for modern Ge device fabrication, which require improved understanding for sub-90nm scaled devices and optoelectronic applications. This work examines the effect of increasing boron or phosphorus dose (i.e. 5×10^{13}-5×10^{16} cm^{-2}) and subsequent annealing (400-800°C for 3 hrs in N_2) on activation and diffusion in Ge using the implant energies of 60 & 170 keV, respectively. In particular, this work presents activation results for implanted peak concentrations above 10^{21} cm^{-3} not previously reported. Secondary ion mass spectrometry (SIMS), spreading resistance profiling (SRP), high resolution X-ray diffraction (HRXRD), X-ray absorption fine structure (XAFS), Rutherford backscattering spectrometry (RBS), and nuclear reaction analysis (NRA) are used to characterize the implant behavior. Unusually high fractions of the boron dose (~5-55%), relative to the Si analog, are incorporated substitutionally immediately after implant leading to very high hole concentrations, $\geq 2\times10^{20}$ cm^{-3}. However, only small increases in activation after anneal are observed and 100% activation is not achieved even after relatively long anneals at 400 or 600°C. Negligible diffusion after annealing was observed for all cases. In addition, reverse annealing (i.e. increase in disorder) at 600°C is indicated by RBS and XAFS measurements, a phenomena also seen for some cases in Si. Phosphorus activation in Ge, alternatively, behaves very differently than boron. Immediately after implant, phosphorus is inactive. Significant crystal damage is detected by RBS after implant, which is largely recovered after anneal. For doses $>10^{15}$ cm^{-2}, the Ge surface is completely amorphised and regrown after 400 and 600°C anneal, achieving crystallinity indistinguishable from unimplanted crystal. For the lowest dose, the crystal is disordered but not completely amorphized. After anneals at 400 & 600°C, phosphorus activation is increased in combination with significant amounts of diffusion for the higher dose cases. The diffusion profiles also show very non-guassian behavior. The highest implant case shows an immobile peak and a relatively long tail of 10^{19} cm^{-3}, which extends deep into the substrate (i.e. 1.5 μm). For the intermediate dose case, a non-gaussian, box-like profile is observed after 600°C annealing. Both profiles are indicative of strongly extrinsic diffusivity (i.e. $D_P \sim (n/n_i)^2$) and a phosphorus solid solubility limited to $\sim 10^{19}$ cm^{-3}. In summary, high concentrations of boron and phosphorus were implanted into Ge (i.e. $>10^{21}$ cm^{-3}) and the activation behavior is compared to lower dose implant. Boron has an exceedingly high solid solubility with no apparently clear limit, even immediately after implant, while in contrast, phosphorus is limited to ~1-2×10^{19} cm^{-3}. Diffusion of phosphorus is extremely extrinsic and fast, while boron is practically immobile.

EE7.21
Silicon Surface Texturization Mechanism by Hydrogen Radicals Using Tungsten Hot Filament. Hiroshi Nagayoshi[1], Suzuka Nishimura[2] and Kazutaka Terashima[2]; [1]Electronic Engineering, Tokyo National College of Technology, Tokyo, Japan; [2]Material Engineering, Shonan Institute of Technology, Kanagawa, Japan.

This paper describes the surface texturing method on crystalline Si using hydrogen radicals generated by a tungsten hot filament. Texturing of silicon surface is a common approach in reducing an optical loss in silicon solar cells. In mono crystalline silicon, excellent light collection can be achieved by forming randomly distributed pyramids on (100) Si wafers using alkaline solution. On the other hand, in the multi crystalline silicon, since only a certain fraction of grains have the required (100) crystallographic orientation, RIE texturing, SF6 and Cl2 are used as reactant gas, mechanical texturisation, and acidic solutions have introduced. However, chemical etching methods generate much chemical waste. In RIE texturing, exhausted SF6 has much higher global warming effect than that of CO2. On the other hand, Cl2 is difficult to handle. We found tungsten particles deposited on Si surface works as an etching mask against hydrogen radicals. Self ordered particle deposition pattern was obtained by increaseing filament current under hydrogen ambient. Surface morphology and feature size of the texture structure could be controlled by the particle deposition condition on Si(100) surface. Inverted pyramid structure was obtained when the particle density was high, suggesting the etching reaction by hydrogen radical is anisotropic. Reflectance spectra of hydrogen treated Si surface using this method showed very low surface reflectance of less than 1% in the range of from 200nm to 900nm without any anti reflection coatings. The particles deposited on silicon surface can easily be removed by HF+HNO3 solution. This method is also effective on the texturing of Si(111) wafer, having a potential for the texturing on multi-crystalline silicon.

EE7.22
Synthesis of visible-photoluminescent silicon nanocrystals embedded in SiO film by pulsed laser annealing.
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In recent years, significant efforts have been focused on the formation and the characterization of Si nanocrystals, due to the unique electronic and optical properties. A nanometer-sized Si crystal exhibits strong room-temperature luminescence when they embedded in SiO_2 layer and have an optical stability suitable for device application. The Si/SiO_2 materials have been prepared via a number of procedures, such as co-deposition of Si and SiO_2, implantation of Si into SiO_2, etc. SiO could be easily ablated by excimer laser beam than SiO_2, which might result in further precipitation of Si nanocrystals by laser annealing. So, we use a SiO target in place of SiO_2. Here, we report on the new method for fabrication of Si-based photoelectric materials by Excimer Laser Annealing of amorphous SiO thin films. The SiO films were prepared by pulsed laser deposition method using a SiO target. We have fabricated Si nanocrystals embedded in the SiO film using KrF excimer laser annealing for the SiO films in high vacuum. The laser annealed SiO films exhibited a sharp Raman peak at 520 cm-1 and synchrotron X-ray diffraction (XRD) pattern of distinct crystalline Si, which indicated the formation of Si nanocrystals in the SiO films. TEM observation also proved the existence of Si nanocrystals with a size of 3-5 nm which agree fairly well with the result of SR-XRD. For the SiO films including Si nanocrystals, strong photoluminescence of red and green have been observed at room temperature.

EE7.23
Characterization of Recessed S/D SiGe on Thin-Body SOI for PMOS Enhancement. David Theodore[1], Peter L. Fejes[1], Michael Canonico[1], Veer Dhandapani[2], Da Zhang[2], Qianghua Xie[1], Bich-Yen Nguyen[2], Pierre Tomasini[3], Chris Werkhoven[3], Chantal Arena[3] and Harry Kirby[3]; [1]Advanced Products R&D Lab, Freescale Semiconductor Inc., Tempe, Arizona; [2]Advanced Products R&D Lab, Freescale Semiconductor Inc., Austin, Texas; [3]ASM America Inc., Phoenix, Arizona.

Semiconductor chip functionality has been doubled approximately every two years by reduction of transistor dimensions. As transistor gate-lengths are reduced to 65 nm, 45 nm and below, novel materials (such as strained Si, SOI, high-k and metal gates) and new novel approaches (such as SiGe stressors, multiple-gate transistors) are needed to further improve transistor performance. Carrier mobilities can be enhanced by the use of strained Si channels, resulting in lifting of heavy-hole light-hole degeneracy in p-type Si, and lifting of the degeneracy of different valleys in n-type Si with consequent suppression of inter-valley electron scattering. Strained Si channels can be generated by global-strain generation or process-induced local-strain generation. Global strain can be generated by methods such as formation of blanket strained Si on relaxed SiGe over a bulk Si or silicon-on-insulator (SOI) substrate. Local strain can be generated by methods such as the formation of recessed source/drain (S/D) SiGe stressors that apply a lateral compressive strain on the Si channel. The use of a compressive strain can enhance p-type carrier mobility in a manner that is useful for PMOS devices. The use of S/D SiGe can contribute to improving contact properties, and the use of SOI substrates can provide improved electrical isolation of devices. In the present work, techniques such as scanning electron microscopy, cross-section transmission electron microscopy, and Raman spectroscopy were used extensively to aid the development of SiGe S/D stressors on SOI substrates for PMOS performance enhancement. The results of SiGe selective-epitaxial growth under different growth conditions, in-situ boron doping, superficial-Si morphology, and varying S/D etching and integration approaches were investigated and will be reported.

EE7.24
Growth of High Quality Ge Epitaxial Layer on Si(100) Substrate Using Ultra Thin SiGe Buffer. Junko Nakatsuru, Hiroki Date, Supika Mashiro and Manabu Ikemoto; Electron Device Equipment Div., ANELVA Corporation, Fuchu-shi, Tokyo, Japan.

Methods for forming Ge epitaxial layer on Si (100) substrate have been vigorously sought due to potential applications of such structure as a virtual substrate for III-V devices on Si. Various methods were proposed to realize low threading dislocation density and smooth surface. To date, such methods involve more than one of thick (micrometer order) SiGe buffer growth process, high temperature annealing steps and CMP process, which could compromise reliability and suitability for production. In this study, we report feasibility of a thin (in the order of 10nm) SiGe buffer layer to realize pure Ge epitaxial layer with good crystalinity, low threading dislocation density, and smooth surface without high temperature annealing steps and CMP process. As a result, we achieved shorter time for growth of practical thickness of crystalline Ge on Si (100) substrate, and also get the high quality Ge epitaxial layer which has low threading dislocation density with very smooth surface. Ge epitaxial layer and underlying thin $Si_{1-x}Ge_x$ buffer layer were grown on Si (100) substrate using a cold wall UHV-CVD system. Source gases of Si and Ge were Si_2H_6 and GeH_4, respectively. No carrier gas was used for this process. SiGe buffer layer was grown on Si(100) substrate at $450-520°C$. Two-step growth process was employed to grow Ge epitaxial layer on the buffer layer. Ge seed layer was grown at a low temperature ($350-400°C$), followed by Ge thick layer growth at a high temperature ($550-650°C$). XRD, TEM, EPD, and AFM were used for characterization of Ge epitaxial layer. Optimization of growth temperature and source gas flow rate ratio enabled to obtain an effective buffer layer thinner than 10nm. The thin buffer layer realizes process time shortening, which is within 10min, and the smooth surface is realized without crosshatch structure. The buffer thickness is 1/160 to 1/1000 than that of previously known methods using thick SiGe buffer layers. Thin SiGe buffer also enabled process time shortening for Ge seed layer growth as two-dimensional Ge layer was formed faster on the thin SiGe buffer layer than on Si. XRD of the Ge seed layer showed 97% relaxation as grown and fully relaxed at 550°C. The threading dislocation density of the top Ge layer was estimated below 1E7counts/cm^2 by TEM and EPD. The misfit dislocations oriented along [110] at the interface between the SiGe buffer layer and the Ge layer, and the distances are 9.5nm constantly in cross-sectional TEM image. We are checking the surface roughness of the Ge epitaxial layer by using AFM.

EE7.25
A Novel Method to Fabricate Recessed SiGe Source/Drain using a selective Si and SiGe Epitaxial Growth without Etching Process. Sang Hoon Kim, Hyun Cheol Bae, Ja Yol Lee and Sang Heung Lee; SiGe Device Team, High Speed IC Research Department, Electronics and Telecommunications Research Institute, Daejeon, South Korea.

Strain-induced modification of the electronic band structures is of great importance to improve the carrier mobility and drive current in metal-oxide-semiconductor field-effect transistors. Among various approaches to introduce strain in the transistor channel region, the technique employing selective epitaxial SiGe in the recessed source/drain region to produce a longitudinal uniaxial compressive stress is introduced to p-MOSFETs in order to increase hole mobility by 50%. On the other hand, the current techniques for formation of the recessed SiGe suffer from degradation of Si crystal quality because the source/drain region is usually dry plasma etched, which would cause damages to the Si surface. For this reason, we present a new fabrication method of recessed SiGe source/drain based on selective Si epitaxial growth, followed by selective re-growth of in-situ doped SiGe without dry etching process. It is composed of two parts. At first, selective epitaxial growth of Silicon was carried at high temperature above 1000C on oxide openings channel region, and then recessed source/drain region was defined using a high wet etch selectivity between thermal oxide and TEOS. For the second step, highly B-doped SiGe was selectively grown at 650C in H2 ambient with SiH4, GeH4 and HCl gases. This fabrication method does not create any defects and surface contamination at the Si surface. Furthermore, the sidewall profile has higher degree of anisotropy in the recessed SiGe source/drain region. In common process, however, it shows isotropic profile with dry plasma etch. The stress becomes more compressive with anisotropic profile than isotropic, which makes this process very attractive for manufacturing. The process has been developed in our standard ASM Epsilon One reactor and investigated by transmission electron microscope and atomic force microscope to characterize of the SiGe source/drain surface morphology. We also evaluated the strain field in a transistor with recessed SiGe source/drain region and examined the lateral and vertical strain components with the dependence of boundary conditions on device structure.

EE7.26
Enhanced fmax and Low Base Resistance in SiGe HBT with Nickel Silicidation. Hyun-Cheol Bae, Sang-Hoon Kim, Young-Joo Song, Seong-Wook Yoo, Sang-Heung Lee and Bo-Woo Kim; Electronics and Telecommunications Research Institute, Daejeon, South Korea.

As the SiGe dense technology advances to deep sub-micron, Ti silicidation has a problem of the resistance increase as the line width reaches the lower sub-micron range. Thus, the Ni silicidation process is appeared to be a suitable candidate to replace Ti silicidation. The SiGe HBT base is composed of a thick cap Si layer, a SiGe layer, and a seed layer. The extrinsic base is formed during Si/SiGe/Si epitaxy, and then nickel is deposited and silicided on the Si/SiGe/Si layer as an interconnection process for the sake of the reduction of contact resistance. Ni silicidation has several advantages over Ti silicidation when used in the SiGe HBT fabrication. The merits are low temperature silicidation process, low sheet resistance, and one step silicidation process. In-situ heavily doped Si/SiGe/Si base layers and other Si epitaxial layers were grown in RPCVD system. Self-aligned Ni silicide on Si/SiGe/Si base was formed in a RTA chamber by one step annealing. A 50 nm thick nickel film which had the lowest value of sheet resistance was then deposited by M2i sputtering system at room temperature. The silicidation reactions were then performed in the RTA system in As ambient for 30s with different annealing temperatures. The nickel layers not reacted on the base were removed by wet etch process after annealing. Ni silicide layers on all electrodes of the emitter, base, and collector of the SiGe HBT were formed simultaneously in a self-aligned manner. Comparing to Ti silicide, the Ni silicide exhibits a lower sheet resistance of under 2 Ω/. In the fabrication of the SiGe HBT, Ni silicide is formed after patterning of the emitter layer. The region below the emitter and of the rest of base are defined the intrinsic base and the extrinsic base, respectively. Ti silicide is formed in the RTP chamber by two step annealing. But, Ni silicide is formed just one step annealing that is performed at 600 oC for 30 sec. REXB of the Ni silicided is below 30% of Ti silicided. The Ni silicided SiGe HBT showed increased fT and fmax values. This means that Ni silicided SiGe HBT has a decreased RB. In terms of the two parameters, the fmax is more sensitively varied with RB. Principally, fT is inversely proportional to the sum of the base transit time, which is influenced by RB, and fmax is significantly increased with the affected factors of fT and RB. The SiGe HBT with Ni silicide reveals about 10% improvement in fT and fmax with respect to the sheet resistance and REXB, that were reduced about 90% and 70%, respectively. Therefore, the base resistance of devices should be reduced to improve fmax. We have fabricated SiGe HBT with Ni silicidation in order to improve the sheet resistance, specific contact resistivity on Si/SiGe/Si base. As a result, we obtained a HBT with low sheet resistance and REXB, which enhanced fmax and fT about 10%. Also, the developed Ni silicide contact technology is suitable for the SiGe BiCMOS process, especially in sub-micron devices.

EE7.27
Kinetically controlled superstructural phases at the Sb/Si (5 5 12) interface. S. M. Shivaprasad[1], Mahesh Kumar[1], Vinod Kumar Paliwal[1] and G Govind[1]; [1]Surface Physics and Nanostructures, National Physical Laboratory, New Delhi, Delhi, India; [2]Surface Physics and Nanostructures, National Physical Laboratory, New

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The adsorption of Sb on the high index Si (5 5 12) has been studied at higher substrate temperature (HT) (800oC), using in situ surface characterization techniques like Auger Electron Spectroscopy (AES), Low Energy Electron Diffraction (LEED), and Electron Energy Loss Spectroscopy (EELS). The surface morphology of this high index Si (5 5 12) surface has row like trenches along 110 direction. We have performed the study of Sb adsorption and desorption on the Si (5 5 12) substrate held at different temperatures. The different pathways adopted during adsorption and desorption have suggested the dominant role of kinetics I forming various surface phases on the Si (5 5 12) substrate. The adsorption at room temperature resulted in the formation of (225) surface phase, while the adsorption at 680oC resulted in the (337) phase. The sequential thermal desorption of the room temperature and high temperature adsorbed surface resulted in the formation of (337) phases at 800oC, with anisotropic growth along one direction. While the adsorption at 800oC resulted in the formation of anisotropic (337) like phases, the further increase in the coverage formed a 2x Si (225) phase. Annealing this 2x Si (225) phase again resulted in the formation of anisotropic (337) phase. Thus formation of interface by controlling the growth kinetics can result in the formation of various tailored structures with desired properties.

EE7.28

Fabrication of Planar SiON Optical Waveguide and Its Characterization. Yu Jung Cho and Yeong-Cheol Kim; Materials Engineering, Korea University of Technology and Education, Chonan, South Korea.

Planar silicon oxynitride (SiON) optical waveguides were fabricated using PECVD (plasma enhanced chemical vapor deposition). Silica (SiO2)-based planar optical waveguides fabricated on Si substrates are becoming key components for optical communication system. Many published works that refer to waveguide structures are based on depositing pure SiO2 for the cladding layer and doped silica, silicon nitride (Si3N4) or SiON for the core layer. The cladding layer has a lower refractive index than the core one. Among materials considered for waveguides, SiO2 is the most promising because of its low cost, low optical loss, and high coupling efficiency with optical fibers. The major advantage of SiON, however, is given by the tunability of the refractive index over a wide range ($n = 1.45 \sim 2$), giving a large degree of freedom to integrated optics design. In this study, SiO2 and SiON films for a planar optical waveguide were deposited by using PECVD from appropriated gaseous mixtures of pure silane (SiH4), nitrous oxide (N2O) and ammonia (NH3). A p-type Si wafer with (100) orientation was used as the substrate. SiO2 and SiON films were obtained at low temperature (300°c) with the variation of RF power and gas flow ratios. SiO2 and SiON films as under-clad and core were deposited with a thickness of 5μm. SiON film was etched selectively by RIE (reactive ion etching). SiO2 film was deposited on the SiON core as over-clad. However, the use of the hydrogen-containing gas in the PECVD method inevitably induces hydrogen-species such as N-H, O-H and Si-H in the core layer, causing harmful absorption loss. Hence, effect of post-annealing on composition and structure of SiON core films was studied by heating the film up to 1000°c in air atmosphere. Refractive index measured by ellipsometry for the SiON films were varied by changing the process parameters. The thickness and surface morphology of the films were characterized by scanning electron microscopy and atomic force microscopy. The light propagation and optical mode of the fabricated 1x4 multi-mode optical splitters were measured using 850nm wavelength laser light.

EE7.29

Thermal Stability of Nickel-Cobalt Multilayer Silicide. Kil Jin Han[1], Yu Jung Cho[1], Hi Deok Lee[2], Soon Young Oh[2], Yong Jin Kim[2], Won Jae Lee[2] and Yeong-Cheol Kim[1]; [1]Materials Engineering, Korea University of Technology and Education, Chonan, South Korea; [2]Electronics Engineering, Chungnam National University, Daejeon, South Korea.

In CMOS technology, transition metal silicides that reduce contact resistance of source/drain have played an indispensable role for high speed semiconductor devices. Among various silicides, titanium silicide and cobalt silicide have been employed in industry. As gate length reduces less than 50nm, however, titanium silicide and cobalt silicide show resistance increase and a new silicide that can show low resistance in a narrow line less than 50nm becomes required. Nickel silicide has become a good candidate for future silicide, as it shows low resistance in a narrow line less than 50nm. Its thermal stability, however, is not enough to be applied as a contact material in industrial process, largely because of the phase transition from nickel monosilicide to nickel disilicide. One of common ways in improving the thermal stability of nickel silicide is to use cobalt-nickel multilayer. However, it has not been known why the multilayer silicide could show the good thermal stability. In this study, we have investigated the structure of nickel-cobalt multilayer silicide to understand its behavior at high temperature. Nickel and cobalt were deposited on B doped p-type (100) silicon substrate sequentially by magnetron sputtering system. Rapid thermal process(RTP) was conducted at 500°C firstly and 700°C secondly under 30mtorr pressure. Before conducting the second RTP, the sample was etched in a chemical to remove the residual metal. The sample was then annealed at 650°C for 30min in a furnace under reduced atmosphere by flowing nitrogen at 15sccm. TEM and XPS were employed to analyze the structure and composition of the nickel-cobalt multilayer silicide. Nickel monosilicide and disilicide are MnP structure and CaF2 structure, respectively. We could observe by TEM that nickel monosilicide is the dominant structure. No Ni-Co-Si ternary phase was detected in this study. We could estimate that nickel-cobalt multilayer silicide forms slower than nickel monosilicide during the high temperature heat treatment and, therefore, indicate that nickel-cobalt multilayer silicide could be more stable at high temperature than nickel silicide.

EE7.30

Modelling of Self-Heating in Strained Si n-Channel MOSFETs on SiGe Virtual Substrates. Rudra Sankar Dhar, Goutam Kumar Dalapati, Sanatan Chattopadhyay, Kelvin Kwa, Sarah Olsen and Anthony O'Neill; School of Electrical, Electronic and Computer Engineering, University of Newcastle upon Tyne, Newcastle, United Kingdom.

Moore's law has been increasingly difficult to maintain in conventional Si technology and strained silicon (strained Si) is being considered to push the boundary for conventional Si complementary metal oxide semiconductor (CMOS) platform. A thin epitaxial film of silicon grown on a relaxed Si1-xGex virtual substrate (VS) is under biaxial tensile strain resulting in enhanced electron and hole mobility. In this work, deep submicron surface channel n-MOSFETs of variable gate lengths with strained Si channel thickness of 6.0 nm on 1.0 μm thick relaxed Si1-xGex virtual substrates ($x = 0.2$, 0.25, and 0.3) have been fabricated. Although, a significant drive current enhancement in the strained Si devices has been achieved in both the linear and saturation regions compared to conventional Si devices, a considerable reduction in drain current in the linear region and a negative slope in the saturation region has also been observed. This reduction in drive current is attributed to self-heating effect in the strained Si MOSFETs fabricated on a thick relaxed Si1-xGex virtual substrate. The thermal conductivity of Si1-xGex alloys is significantly lower than that of Si and it decreases with increasing Ge content in the alloy. Thus, during the dc operation of the device, the strained Si n-channel MOSFETs on Si1-xGex VS experiences a significant temperature rise due to self-heating, and as a consequence, the drive current is reduced. It is therefore necessary to understand and model the challenges posed by self-heating in strained Si devices, prior to its implementation in real circuit applications and mass production. The variation of thermal resistance and thermal healing length has been derived for different VS thickness and also for various Ge contents. The self-heating effect has been modelled considering the heat flow equations and thermal resistance in the channel. The amount of generated heat, and hence the temperature, varies with Ge content and the maximum temperature rise is obtained to be 625 K for a 30% Ge in the VS @ $W/L = 10\ \mu m/0.7\ \mu m$. An analytical drain current model has also been predicted using the estimated rise in temperature due to self-heating with the inclusion of parasitic source - drain (Rsd) resistance. The model is proved to be accurate when compared with experimental drain current - drain voltage (Ids-Vds) characteristics.

EE7.31

Abstract Withdrawn

EE7.32

X-Ray Absorption Measurements of Strained-Silicon-on-Insulator(sSOI). Zhiwei Li[1], Fan Zheng[2], Franz J. Himpsel[2], Donald E. Savage[1], Xiaosong Liu[2] and Max G. Lagally[1,2]; [1]Material Science Programm, Univ. of Wisc.-Madison, Madison, Wisconsin; [2]Physics Department, University of Wisconsin-Madison, Madison, Wisconsin.

Because of a large enhancement of the mobility of electrons, strained silicon (sSi) permits a significant improvement in the performance of electronic devices. Much work has been done on the compressively strained silicon-germanium alloys, but relatively few results exist on the electronic structure of tensilely strained silicon. We present a comparison of x-ray absorption measurements of tensilely strained Si-on-insulator (sSOI) and Si-on-insulator (SOI). We find that, although the conduction band minimum (CBM) splitting and shift match theoretical predictions and other measurements, the 2p core level also shifts due to the strain, soemthign that had not been observed or expected. Because x-ray absorption measures the density of empty states in the top several nanometers of a material, it is ideal

for measuring the state of strain on the surface.. We relate our relate our results to our ongoing work on elastically relaxed free-standing membranes made from SiGe/Si layers. [1] [1] M. Roberts et al., in preparation Research supported by NSF MRSEC. Research conducted at the Synchrotron Radiation Center, University of Wisconsin-Madison, which is supported by the NSF under Award No. DMR-0084402

EE7.33

Element Distribution and Spacial Crystallinity of Catalyst in β-Ga2O3 Nanowires Grown in Vapor Reaction. Yucheng Lan, Martin A. Crimp and Jiaming Zhang; Michigan State University, East Lansing, Michigan.

We have used advanced energy dispersive X-ray spectroscopy (EDS) techniques to study the element distribution and selected area electron diffraction (SAD) technique to investigate the crystallinity of β-Ga2O3 semiconductor nanowires. EDS mapping indicates the catalyst locates at tip of nanowires. X-ray linescans show catalyst also extends into Ga2O3 nanowires beyond tip to form a interface between Ga2O3 nanowire and catalystic tip. Combining SAD and EDS quantitative analysis, continuous solid-solution regions are observed at catalystic tip surface and the termination of nanowires. Based on the assumption that nanowires grow from solid-solution, a mechanism for the nanowire growth is proposed. The new grow mechanism explains well the element distribution and different crystallinity along nanowires. Crystallinity of the nanowires is also examined by high resolution transmission electron microscopy.

EE7.34

Semiconductor Nanotemplates for Nanofabrication. Ion Tiginyanu[1,2], Eduard Monaico[2], Lilian Sirbu[2], Sergiu Albu[2], Veaceslav Ursaki[1,2] and Robert W. Boyd[3]; [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; [3]Institute of Optics, University of Rochester, Rochester, New York.

In contrast with high-resistance porous alumina, semiconductor nanotemplates may play an active role in nanofabrication. In particular, the semiconductor component can be responsible for the high conductivity of polymer-semiconductor nanocomposites fabricated by filling in the pores with polymers. Taking into account the compatibility with microelectronic technologies, semiconductor nanotemplates are promising for application as substrates for nanoheteroepitaxy of high-quality materials. In this report, we present results of development and characterization of semiconductor nanotemplates based on II-VI compounds such as ZnSe and CdSe using electrochemical and chemical wet etching techniques [1]. Ordered spatial distribution of nanochannels is reached due to self-arrangement phenomena. Development of ZnSe nanotemplates transparent in the visible region is of peculiar interest. We demonstrate the possibility for nanostructuring ZnSe substrates in a controlled fashion. Note that the chemical composition of the porous skeleton corresponds to ZnSe. 2.5D semiconductor periodic structures are explored as well, using the possibility to modulate the diameter of pores in a periodic fashion. Layers and free-standing membranes with the pore diameter ranging from 40 to several hundreds of nanometers can be fabricated using the proposed technology. According to our results of photoluminescence characterization, the nanotemplates based on ZnSe and CdSe are promising materials for the development of random lasers. We show the possibility to cover the internal surface of nanostructured layers and membranes by metal dots and thin films using novel chemical-electrochemical approaches [2]. This work was supported by the U.S. Civilian Research and Development Foundation under Grants nos. MR2-995 and ME2-2527. [1] I.M. Tiginyanu et al, Appl. Phys. Lett. 86, 063115 (2005); [2] A.I. Dikusar et al, Electrochem. Sol.-State Lett. 8 (3), C51 (2005).

EE7.35

MnAs Nanocluster Formation on GaInAs/InP (111) Layers Grown by Metal-Organic Vapor Phase Epitaxy. Shinjiro Hara and Takashi Fukui; Research Center for Integrated Quantum Electronics (RCIQE) and Graduate School of Information Science and Technology, Hokkaido University, Sapporo, Japan.

Ferromagnetic nanoclusters hybridized in III-V compound semiconductors (FM III-V hybrids) and III-V compounds-based diluted magnetic semiconductors are very promising for realising nano-spintronic devices using not only the charge but also the spin of carriers. In MnAs/GaAs materials system, which has been most intensively investigated, MnAs thin films are grown on GaAs layers by molecular beam epitaxy (MBE). We have pursued FM III-V hybrids, in particular, using MnAs nanoclusters embedded in GaInAs/InP (001) layers grown by metal-organic vapor phase epitaxy (MOVPE) [1, 2]. In this work, we demonstrate MOVPE growth and the successful formation of novel MnAs nanocluster structures on GaInAs/InP (111) surfaces. (111) crystallographic orientations of zinc-blende structures are promising not only for the growth of catalyst-free semiconductor nanowires using selective area MOVPE [3] but also for the formation of MnAs nanoclusters with NiAs-type hexagonal crystallographic structures. Tri-methyl-gallium (TMGa), tri-methyl-indium (TMIn), tertiary-butyl-phosphine (TBP) and arsine (AsH_3) were used as source materials for the MOVPE growth of GaInAs and InP. *Bis*-(methyl-cyclopentadienyl) manganese ($(MeCp)_2Mn$) was chosen as a manganese organometallic precursor. After the growth of GaInAs layers on InP buffer layers, $(MeCp)_2Mn$ was introduced to the MOVPE reactor with AsH_3. All the layers were grown at 600 °C on InP (001), (111) A and B wafers. Atomic force microscopy (AFM) was used to closely investigate structural characteristics of MnAs nanoclusters. Initially, GaInAs layers grown on InP buffer layers were confirmed to have a stepped surface without any nanoclusters by AFM. However, we find that nanoclusters are formed on GaInAs/InP (001), (111) A and B surfaces after the growth of MnAs. Hexagonal nanoclusters with well-defined crystallographic facets with respect to the growth substrates are formed on (111) A and B surfaces, whereas rectangular nanoclusters on (001) surfaces. Hexagonal shape of the nanoclusters on (111) surfaces is presumably due to NiAs-type hexagonal crystallographic structures of MnAs. The typical nanoclusters measured about 330 nm in diameter and 6 - 20 nm in height. On (111) B surfaces, in particular, by increasing a partial pressure of $(MeCp)_2Mn$ in a supply gas, the lateral size of the nanoclusters is increased, whereas almost no change in height. The nanoclusters observed on (111) B surfaces are mostly elongated toward a [110] direction. The experimental results in this work, therefore, indicate that MnAs nanoclusters are grown two-dimensionally on (111) B surfaces after the nucleation of nanoclusters. The size of MnAs nanoclusters on GaInAs/InP (111) surfaces can be controlled by changing partial pressures of $(MeCp)_2Mn$ during MOVPE growth. [1] S. Hara *etal*, J. Cryst. Growth, **261**, 330 (2004), [2] S. Hara *etal*, Nanotechnology, **16**, 957 (2005), [3] J. Motohisa *etal*, J. Cryst. Growth, **272**, 180 (2004).

EE7.36

Platinum Nanoparticles as the Charge Storage for Nano-Floating Gate Memory Application. Byoungjun Park, Dong-Won Kim, Hyunsuk Kim, Samjong Choi, Kyoungah Cho and Sangsig Kim; Electrical Engineering, Korea University, Seoul, South Korea.

The charge storage effect in platinum nanoparticles (Pt NPs) synthesized by using an alcohol reduction have been investigated. The synthesized PVP-Pt NPs (~4nm in size) were confirmed by high resolution transmission electron microscopy. PVP-Pt NPs acting as the roles of charge stroge nodes have been incorporated into a metal-oxide-semiconductor (MOS) structure (p-Si/SiO2/Pt NPs/Al2O3/Al) for nano-floating gate memory. The characteristics of current and capacitance versus voltage were measured. The fabricated devices showed low level leakage current density (~25.4nA/cm2 at 10V) and exhibited large hysteresis loop (ΔVth = ~13V) in capacitance-voltage (C-V) curve compared with the device without Pt NPs. This result was caused by the charge storage effect of Pt NPs embedded in oxide layers. The direction of hysterisis loop in C-V curve depending on the sweep and stress condition was also investigated.

EE7.37

Properties of Electro-Luminescence Devices with Silicon Nano-Crystals Prepared by Laser Ablation Method as a Light Emitting Material. Akira Sugimura, Motohiko Koyama and Ikuro Umezu; Department of Physics, Konan University, Kobe, Japan.

Silicon nano-crystal material has attracted much interest because of its applicability to future light emitting devices, although its properties are still necessary to be improved. Previously, we showed that Si nano-crystals prepared by the laser ablation method in the hydrogen atmosphere provide us good quality, high efficiency photo-luminescence (PL) when the ablation conditions are optimized [1]. Thus, we fabricated electro-luminescence (EL) device structures with this Si nano-crystal material and studied their optical and electrical properties in order to investigate device performance limits caused by the materials used in the EL device. The fabricated device structure is as follows. Si nano-crystal layer is prepared by aluminum electrode. It is then capped by indium tin oxide (ITO) material [2], which is contacted to the other electrode. Isolations between devices and electrodes are made with SiO2 spacer regions. We fabricated and studied various types of devices of the active region. From the EL device fabricated using the optimized condition, we observed intense and visible light emission at room temperature, when the input current is as high as sub-milli-amperes. The peak wavelength of the emission spectrum of the present device is about 900nm, which is longer than that of the photo-luminescence spectrum of the Si nano-crystals prepared by the same method. We measured current-voltage characteristics, which indicate non-linear and irreversible dependences. It is found that optical output intensity

indicates linear dependence on the electric current in the weak current region, while it transfers to the square dependence when the current exceeds a certain value. These behaviors indicate that the impact ionization by accelerated electrons plays an important role in creating electrons and holes in the device. Degradation of LED optical output power is also studied. It is found that the degradation is caused by the decrease of the current, and this decrease is originated from the oxidation of the Si nano-crystal surfaces. In conclusion, we studied the properties of the EL device with Si nano-crystal active layer and found that the device performance strongly depends on the electrical properties of the nano-crystal layer as welll as its optical properties.
[1]M.Inada et al., Materials Science & Engineering B 101(2003) 283.
[2]T. Yoshida et al., J. Appl.Phys., 63, (1998)5427

EE7.38
Self-Assembled Growth of Semiconductor Nanostructures for Electrical and Optoelectronic Applications. Ghim Wei Ho[1], Andrew See Weng Wong[2], Dae Joon Kang[1] and Mark E. Welland[1]; [1]Nanoscience Centre, University of Cambridge, Cambridge, Cambridge, United Kingdom; [2]Department of Materials Science and Metallurgy, University of Cambridge, Cambridge, Cambridge, United Kingdom.

Control of size and dimensionality of nanostructure to tune its properties has already been shown, however to date no reports have demonstrated the ability to control both the dimensionality of the nanostructures and the assembly of the nanostructures into a highly ordered system. Here we report a vapor based approach to control the morphology in addition to the ability of self-assembling semiconductor ZnO and SiC nanostructures into a metamorphosis of architectures. By observing the fundamental crystallographic design rules and using template, we can organize multi-dimensional ZnO and SiC building blocks into a hierarchical heterostructure arrays. The synthesis of different dimensions and morphologies of ZnO nanostructures were carried out by simple thermal evaporation of a mixture of graphite and ZnO while the synthesis of SiC nanostructures were carried out using methane gas and Si powder. Coaxing these semiconductor nanostructures into self-assembling is an avenue that we are exploring since the traditional fabrication methods are limited in resolution. Unlike the artificially ordered system, such as the existing integrated circuits technology, self-assembled processes allow the creation of complex device architectures which depends solely on the intrinsic ability to organize itself into ordered system. Thus this method provides a promising route to integrate multi-dimension nanostructures into the future generation of complex nanodevices which would otherwise be very difficult to fabricate directly. Both electrical and optical properties can be derived from the as-grown semiconductor nanostructures whereby the potential of fabricating transistor device can be realized with its well-defined linear I-V characteristics as well as feasibility of fabricating optoelectronic devices can be shown with the significant UV light emission.

SESSION EE8: Zinc Oxide Materials and Devices Including Alloys I
Chairs: Mike Callahan and Andrei Osinsky
Wednesday Morning, November 30, 2005
Constitution B (Sheraton)

8:00 AM EE8.1
Vacancy defects in electron-irradiated ZnO. Filip Tuomisto[1], Kimmo Saarinen[1], David C. Look[2] and Gary C. Farlow[3]; [1]Laboratory of Physics, Helsinki University of Technology, TKK, Finland; [2]Semiconductor Research Center, Wright State University, Dayton, Ohio; [3]Physics Department, Wright State University, Dayton, Ohio.

Due to recent progress in crystal growth and unique piezoelectric, optical and electrical properties, zinc oxide (ZnO) can be considered as a serious alternative to gallium nitride (GaN) for use in optoelectronic devices. The microscopic processes behind the high radiation hardness of ZnO need to be fully understood in order to uncover all the potential applications of the material. The role of vacancies in both self-compensation and the high radiation hardness can be determined by positron annihilation. Our earlier positron studies have shown that the Zn vacancy acts as a domi-nant compensating center in as-grown n-type ZnO [1]. Here we have used positron annihilation spectroscopy to study the introduction and recovery of vacancy defects in electron-irradiated n-type ZnO. The irradiation (E_{el} = 2 MeV, fluence 6×10^{17} cm^{-2}) was performed at room temperature and isochronal annealings were performed from 300 to 600 K. In addition, we used monochromatic illumination of the samples during low-temperature measurements. We distinguish vacancy defects on both the Zn and O sublattices. In addition, we observe negative ion type defects, which are attributed to O interstitials or O antisites. The Zn vacancies and negative ions act as compensating centers and are introduced at a concentration $[V_{Zn}] \cong c_{ion} \cong 2 \times 10^{16}$ cm^{-3}. The illumination experiments show that both the Zn vacancies and the negative ion defects have an ionization level close to 2.3 eV. The O vacancies are introduced at a 10 times higher concentration $[V_O] \cong 3 \times 10^{17}$ cm^{-3} and are suggested to be isolated. The O vacancies are observed as neutral at low temperatures and an ionization energy of 100 meV could be fitted with the help of temperature dependent Hall data, thus indicating their donor character. The irradiation-induced defects fully recover after the annealing at 600 K, in good agreement with electrical measurements. The Zn vacancies recover in two separate stages, indicating that two different defect complexes are involved in their recovery. The O vacancies anneal simultaneously with the Zn vacancies at the later stage, with an activation energy of $E_A = 1.8(1)$ eV. The negative ions anneal out between the two annealing stages of the vacancies. [1] F. Tuomisto, V. Ranki, K. Saarinen, and D. C. Look, Phys. Rev. Lett. 91, 205502 (2003).

8:15 AM EE8.2
Photoluminescence investigations on a native donor in ZnO. Bruno Meyer, Joachim Sann, Stefan Lautenschlaeger and Niklas Volbers; 1. Physikalisches Institut, Giessen, Germany.

The shallow donor impurities in ZnO with binding energies between 46 and 56 meV have been studied in great detail in the recent years. They give rise to neutral donor bound exciton recombinations with the A- and B-valence bands, show rotator states and two-electron-satellite transitions. These properties allowed to establish the excited state splittings of the donors as well as confirming Hayne's rule in ZnO. So far they all seem to be of extrinsic origin, hydrogen, aluminum, gallium and indium in order of increasing binding energy. For many years it was common sense that intrinsic defects would dominate the n-type conductivity of ZnO. Interstitial zinc as well as oxygen vacancies should be double donors, and in order to contribute to the n-type-conduction they should have shallow levels, and low formation energies to be abundant. In PL-measurements at T$\sim$100 K on various ZnO samples, single crystals as well as thin films, a luminescence around 3.31 eV was detected. Due to its line shape and temperature behaviour it is identified as bound-to-free recombination. If we assume that the 3.31 eV band with its level at EC $\sim$ 130 meV is the ++/+ level of the zinc interstitial we calculate for the binding energy of the +/0 level 0.25 * 130 meV, i.e. around 33 meV. Undoped Zn-rich epitaxial films grown by CVD show a dominant I3 recombination at 3.367 eV which according to Haynes rule is consistent with a shallow donor level at 33 meV. Moreover, they have free n-type carrier densities of 2x1019 cm-3 and as revealed by SIMS the common donor impurities (Al, Ga, In) cannot account for the high carrier densities.

8:30 AM EE8.3
Complex Formation in Undoped and Nitrogen Doped Zinc Oxide Grown by MOCVD. N. H. Nickel[1], F. Friedrich[1], J. F. Rommeluere[2] and P. Galtier[2]; [1]Hahn-Meitner-Institut Berlin, Berlin, Germany; [2]CNRS-LPSC, Meudon, France.

Research on zinc oxide (ZnO) is driven by a strong desire for blue and ultraviolet light emitting devices. So far, however, the major shortcomming is the lack of reliable p-type doping. In this paper, we present a detailed investigation of undoped and nitrogen doped ZnO layers using vibrational spectroscopy. The specimens were grown in a horizontal commercial MOCVD reactor at atmospheric pressure using dimethylzinc and tertiarybutanol as zinc and oxygen sources. Nitrogen doping was achieved by adding diallylamine and the carrier gas was hydrogen. The ZnO layers had a thickness of 0.8 to 2.2 μm and were characterized using Fourier transform infrared spectroscopy and Raman backscattering. Both, undoped and nitrogen doped ZnO layers revealed broad vibrational modes at 1414 and 1585 cm^{-1}. These lines indicate the presence of carbon sp^2 clusters. In nitrogen doped ZnO the lines are more pronounced than in undoped samples. Furthermore, in N doped ZnO a new local vibrational mode near 2000 cm^{-1} is observed that most likely originates from the formation of Zn-H complexes. Infrared measurements reveal the presence of cyano radicales (CN) and a large amount of CO_2 molecules. The presence of these defects and clusters suggests that chemical reactions of the metal organic precursors in the gas phase play a critical role for controlling impurity and dopant concentrations. The implications for achiving reliable p-type doping of ZnO will be discussed.

8:45 AM EE8.4
Role of Active Oxygen Species on Growth of ZnO Using RF-PAMBE. S. M. Durbin[1], W. C. T. Lee[1], M. Allen[1], P. Miller[2] and R. J. Reeves[2]; [1]Electrical & Computer Engineering, University of Canterbury, Christchurch, New Zealand; [2]Physics, University of Canterbury, Christchurch, New Zealand.

The basic ZnO RF plasma-assisted molecular beam epitaxy (RF-PAMBE) growth technique is essentially identical to what has been successfully implemented for the nitride semiconductor family, and there is every reason to expect differences in moving to a different material system. For example, it is reasonably well-established that

the key species produced efficiently by nitrogen RF plasma sources is N_2*, with evidence that atomic nitrogen can have deleterious effects on growth. The highest quality material is often grown at reduced RF power, and with a Ga bilayer riding the surface. In contrast, there is evidence that O* plays the major role in growth of ZnO using the same basic technique, and an improvement is generally seen in film quality for increased RF power. Little is known, however, about the importance or effects of the variety of neutral and ionised oxygen species produced by these plasma sources on properties of ZnO thin films. In this study, a series of ZnO thin films were grown on (0001) sapphire substrates at a temperature of 650°C. Prior to nucleation, a ~50 nm buffer layer was grown at 300°C. Active oxygen was supplied using an Oxford MDP21 plasma source with an aperture configuration of 276 0.2 millimetre diameter holes. RF power was varied over the range of 60 to 400 W, with a Zn flux of approximately 7×10^{14} atoms/cm^2·s. The plasma discharge was characterised optically through the rear window port of the plasma source using a Jobin Yvon CCD-3000 spectrometer. Films were analysed using in-situ reflection high-energy electron diffraction, scanning electron microscopy, atomic force microscopy, photoluminescence (excited by 333 nm argon ion laser line) and Hall effect. Regardless of RF power, a sharp 777 nm triplet due to O* as well as a distinct O_2* band at 760 nm were consistently observed. However, the intensity ratio of these features changed markedly as a function of applied power, with proportionally more O* present with increasing power until approximately 300 W, after which it levels off. Depending on the flow rate, this intensity ratio is observed to decrease in some cases for powers above 300 W. Interestingly, an order of magnitude increase in growth rate was observed between films grown at 150 W and those grown at 300 W, matched well by an observed 12-fold increase in the O* intensity. In contrast, the intensity of the O_2* band increased only 5-fold over the same RF power range, suggesting that O* plays the major role in growth, although O_2* may still play a secondary role. Film quality was observed to improve significantly as a function of RF power, with the film grown at 400 W characterised by a comparatively flat surface, streakier RHEED, and a carrier concentration a full order of magnitude lower than that grown at 150 W. This is consistent with earlier reports of improved growth at higher RF powers, but the relatively small change in both O* and O*/O_2* ratio between 300 W and 400 W suggests a more complex mechanism.

9:00 AM *EE8.5
Electrical and Optical Activity of Point Defects in ZnO.
David C. Look[1,2], Gary C. Farlow[3], Sukit Limpijumnong[4], Shengbai Zhang[5] and Kai Nordlund[6]; [1]Semiconductor Research Center, Wright State University, Dayton, Ohio; [2]Materials and Manufacturing Directorate, Air Force Research Laboratory, Wright-Patterson AFB, Ohio; [3]Physics Department, Wright State University, Dayton, Ohio; [4]School of Physics, Suranaree University of Technology, Nakhon Ratchasima, Thailand; [5]National Renewal Energy Laboratory, Golden, Colorado; [6]Accelerator Laboratory, University of Helsinki, Helsinki, Finland.

The role of point defects in determining the electrical properties of ZnO has been a source of much speculation over the last several decades. For example, as-grown ZnO is nearly always n-type, with Zn-rich stoichiometry, so early researchers almost universally attributed the background donors to either the O vacancy $V_{O|}$ or the Zn interstitial Zn_I. This situation prevailed until the year 2000, when Kohan et al. showed theoretically that both $V_0{}^+$ and $Zn_I{}^+$ have high formation energies in n-type ZnO, and thus are not likely to exist in significant quantities. Furthermore, they found that V_O is a deep donor, and so wouldn't contribute free carriers in any case. Van de Walle then showed theoretically that the H interstitial $H_I{}^+$ has a much lower formation energy than that of either $V_O{}^+$ or $Zn_I{}^+$ in n-type material and thus is a much more likely candidate for the main background donor, especially since H is often present in a typical ZnO growth environment. Several experimental groups have since verified that H is a donor and is often present in as-grown ZnO, and thus prevailing opinion is now that point defects do not play a significant role as background donors. However, we will show here that a particular point defect, Zn_I, indeed does contribute to n-type conductivity, but as a complex, not as an isolated entity. To reach this conclusion, we have irradiated high-quality bulk ZnO samples with 1-MeV electrons to create Zn_I and V_O defects, and have studied their properties with temperature-dependent Hall-effect and low-temperature photoluminescence (PL) measurements. We have also used molecular dynamics (MD) simulations to calculate the production rate of the Zn_I, and density functional theory (DFT) to calculate the energetics of a particular complex, Zn_I-N_O. This complex can be formed in our material because of a high N background, and DFT shows that it has a shallow donor character as well as a relatively low formation energy. From the Hall-effect results, we find that the irradiation produces a 30-meV donor, and its concentration is consistent with that of Zn_I as predicted by the MD simulations. From the PL data, we find a new, sharp, donor-bound exciton (D^0X) line at 3.36070 eV, and two-electron satellite (TES) lines at 3.33711, 3.33793, and 3.33840 eV, consistent with a 30-meV hydrogenic-type donor. We suggest that this donor is the Zn_I-N_O complex. Annealing at 400 °C returns the electrical properties to their pre-irradiation state, and the new PL lines also largely disappear. Since the as-grown material also clearly contains a 30-meV Hall-effect donor and two of the three TES lines, we suggest that Zn_I-related donors can be important in as-grown ZnO. We note that previous studies have shown that another defect, the Zn vacancy V_{Zn}, is a dominant acceptor in as-grown, n-type ZnO. Thus, contrary to present thought, we conclude that native point defects are important both as donors and acceptors in n-type ZnO.

9:30 AM EE8.6
Thermal stability of ion implanted ZnO. Victoria Coleman[1], H. H. Tan[1], C. Jagadish[1], S. O. Kucheyev[2], J. Zou[3] and M. R. Phillips[4]; [1]Department of Electronic Materials Engineering, Australian National University, Canberra, Australian Capital Territory, Australia; [2]Lawrence Livermore National Laboratory, Livermore, California; [3]School of Engineering and centre for Microscopy and Microanalysis, The University of Queensland, St Lucia, Queensland, Australia; [4]Microstructural Analysis Unit, The University of Technology, Sydney, Broadway, New South Wales, Australia.

With a large exciton binding energy and wide band gap, ZnO is a very attractive material for a range of (opto)electronic devices including blue light-emitting diodes and laser diodes. However, before ZnO devices containing p-n junctions can be realized, the challenge of reliably and reproducibly achieving p-type doping in this material must be overcome. Ion implantation is widely used in the microelectronics industry for selective area doping, device isolation and quantum well intermixing. A thorough understanding of damage accumulation, recrystallization processes and thermal stability is important for achieving all of these aims. In this study, the thermal stability of ZnO implanted with very high dose (1.4 X 10^{17} cm^{-2}) 300 keV As ions (potential p-type dopant) in the range 77 K − 500 K is investigated. Post implantation annealing of samples in the range of 1000 − 1200 ^oC was employed to recover the crystallinity of the heavily damaged layers. Rutherford backscattering/channelling spectrometry, transmission electron microscopy and atomic force microscopy revealed that heavily damaged ZnO is not thermally stable and evaporates at high temperatures, whilst the undamaged ZnO remains unaffected. An optimum set of conditions for achieving recrystallization and dopant activation without loss of material has thus been derived and applied to both N^+ and P^+ implants into ZnO for p-type doping, as well intermixing studies of ZnO/ZnMgO quantum well samples. The results of this study have significant implications for ZnO-based devices, particularly the creation of p-type material by ion implantation. Work at LLNL was performed under the auspices of the U.S. DOE by University of California, LLNL under Contract W-7405-Eng-48.

9:45 AM EE8.7
UV photoconductors based on Ga-doped ZnO films.
Leelaprasanna J. Mandalapu, Faxian Xiu, Zheng Yang and Jianlin Liu; Department of Electrical Engineering, University of California, Riverside, Riverside, California.

ZnO is a wide bandgap (3.37eV) semiconductor that is being explored widely in recent years for UV optoelectronic applications such as photodetectors and LED devices because of its attractive and promising properties. Attempts are being continuously made to grow high quality ZnO films and fabricate various kinds of ZnO based photodetectors such as photoconductors, hetero-junction and homo-junction photodiodes, thin film transistors, surface acoustic waveguide photodetectors, etc. Reproducible *p*-type doping remains challenging to obtain reliable high performance from some of these devices. In our study, we report the successful fabrication of high quality photoconductors based on Ga-doped *n*-type ZnO. The ZnO films were grown by molecular beam epitaxy on R-plane sapphire substrates. Material characterizations such as photoluminescence (PL), X-ray diffraction (XRD), reflection-high energy electron diffraction (RHEED) and Hall measurements were carried out, which indicated a single crystal ZnO film growth on sapphire with an orientation of (1120). Hall measurement results showed *n*-type ZnO films with a carrier concentration of the order of 10^{18} cm^{-3} and low resistivity of 0.07 Ω-cm to 0.19 Ω-cm. Device fabrication was done by standard photolithography techniques. A set of samples was fabricated by defining mesas of area 250 μm × 250 μm and 500 μm × 500 μm and another by directly depositing metal. Al (400nm)/Ti (20nm) ohmic contacts were made by e-beam evaporation and lift off. Wet chemical etching was employed to define mesas. Linear characteristics were obtained from Current-Voltage (I-V) measurements that also showed response to UV illumination. Voltage dependent photocurrent characterization was carried out after packaging the devices. The detection restricted to UV region was observed. The response extended from UVA (400-320 nm) to UVB (320-290nm) region and partially into UVC (220-290 nm) region with

a peak position in the UVA region. Responsivities and quantum efficiencies were also estimated.

10:30 AM EE8.8
Stabilization of mixed valencies in Cu, Zn-based oxides.
Anne Le Nestour[1], Manuel Gaudon[1], Mona Treguer-Delapierre[1], Ronn Andriessen[2] and Alain Demourgues[1]; [1]ICMCB-CNRS, Pessac Cedex, France; [2]AGFA-Gevaert, Mortsel, Belgium.

Cu and Zn-based oxides have been developed for the last decades because of their remarkable electronic properties and their relevant UV-Visible-NIR absorption properties. Cu in oxides can adopt various oxidation states (+I, +II, +III) stabilized in various environments (D∞h, Td, D4h, C4v, D2h, Oh). Divalent copper cations can occupy Td or Oh sites in zinc aluminate spinel network. Solid state routes lead to homogeneous phases with Zn1-xCuxAl2O4 compositions. Depending on the inversion rate in the spinel matrix, various absorption bands have been identified in the UV-Visible-NIR spectrum. The synthesis of the zinc-aluminate spinel solid solution Zn1-xCuxAl2O4 by an esterification route led to monocrystalline nanosized oxides. Two intense absorption bands at 300 and 500 nm can be attributed to charge transfer phenomena between oxygen and Cu2+ cations in tetrahedral and octahedral coordinations. Two other less intense absorption bands centred at 800 nm and 1500 nm are also appearing when the copper rate in the spinel increases but their relative intensity are not in good agreement with those observed in the case of the solid-state synthesis. In the case of the esterification route, the absorption band at 800 nm is much more intense than in the case of the solid-state synthesis. It can only be explained either by a deviation to the centrosymmetric character of octahedral sites or by the occurence of a non negligible amount of monovalent copper cations which give electronic transitions in this energy range. A magnetic study correlated to EPR measurements confirms the occurence of a mixed valence state for copper cations in the solid solution Zn1-xCuxAl2O4. EPR spectra at T=4K show for the small concentration of Cu2+ (x<0.10) a strong anisotropic signal due to the presence of Cu2+ ions in a distorted octahedral symmetry (gx=2.07, gy= 2.15 gz=2.23). Moreover the hyperfine structure, identified on EPR spectra tends to disappear as the compounds are annealed under air because the content of paramagnetic centers Cu2+ (3d9) as well as their interactions become significant. Furthermore, the color changes drastically with the Cu+ (3d10) content. Finally the *structural features and UV-Visible-NIR absorption properties of copper-zinc aluminates* will be discussed and compared to *Cu-doped ZnO.*

10:45 AM EE8.9
Acceptor related Luminescence in ZnO. Frank Bertram[1], Juergen Christen[1], Soeren Giemsch[1], Thomas Hempel[1], Silke Petzold[1], Armin Dadgar[1], Alois Krost[1], Axel Hoffmann[2] and Markus Wagner[2]; [1]Institute of Experimental Physics, Magdeburg University, Magdeburg, Germany; [2]Institute of Solid State Physics, Technical University Berlin, Berlin, Germany.

Despite many years of extensive studies, some of the essential properties of the luminescence in ZnO are still not fully understood. One of the poorly understood issues is the acceptor related luminescence in ZnO. We present a comprehensive analysis of the optical properties of a nominally undoped, i.e. n-conducting ZnO epitaxial layer by means of temperature dependent photoluminescence (PL) and scanning cathodoluminescence (CL) microscopy. The thick ZnO epi-layer under study was grown by metal organic chemical vapor phase epitaxy on a GaN/sapphire template using a 0.3μm thick ZnO buffer deposited at 450°C and in situ annealed at 900°C inside the reactor. The final nominally 8μm thick ZnO layer was subsequently grown at 900°C. The spatially averaged luminescence spectrum is dominated by the impurity bound exciton I8. The free exciton XA, the bound excitons I0, I2, I6, and I9, as well as LO phonon replica of I8 can be clearly obtained at low temperatures. Additionally the two electron satellites (TES) of I8 and I9 are also visible in the near band gap region. All lines are 0.7meV red shifted with respect to their fully relaxed position known from bulk crystals indicating minor tensile strain. At 4K the TES I8 and I9 lines are well separated and easy to identify. At elevated temperatures (T=70K) a new broad peak shows up precisely at the spectral position of these TES peaks E=3.305eV. This line exhibits a pronounced high energy Boltzman tail and up to 5 LO phonon replica at the low energy side. With increasing temperature this line together with its LO replica become dominant. Due to the temperature dependence of intensity and spectral shift we assign this line to free to bound transition (e,A^0). We are able to determine an acceptor binding energy of EA=130meV from the energetic position of this transition. Highly spatially resolved CL mappings visualize surface defects (hexagonal craters) as the localized origin of the (e,A^0) emission. For a verification of our assignment we took temperature dependent CL spectra from the same identical two sample positions: from a spot in the matrix and from a specific crater. With increasing temperatures the (e,A^0) transition relatively increases in intensity at both positions, however, it gains significantly more at the defect region. Even more (e,A^0) dominates the local spectrum from the defect spot for T>150K, while I8 is still dominant at the matrix spot and the integral spectrum. This strongly suggests an acceptor accumulation in the vicinity of the morphological defects. The nature of the exciton binding centers is determined using magneto-optics in emission and absorption. Thermalization data provide information of the bound exciton recombinations to be donor or acceptor related. The angular dependent Zeeman splitting gives further evidence for the interpretation of the bound exciton transitions.

11:00 AM EE8.10
Hydrothermal ZnMgO bulk crystals. Michael J. Callahan[1], Buguo Wang[2], Lioniel Bouthillette[1], Michael Suscavage[1] and Sheng-Qi Wang[2]; [1]SNHC, Air Force Research Lab, Hanscom AFB, Massachusetts; [2]Solid State Scientific Corporation, Nashua, New Hampshire.

The ZnMgCdO alloy system has certain advantages over the AlGaInN alloy system such as: higher exciton binding energies; ability to grow direct bandgap alloys from green-UV with a smaller change in lattice constants; lower growth temperatures; and faster etch rates. Despite these advantages efficient ZnO based LEDs and laser diodes have not been demonstrated because of the inability to obtain p-doped ZnO thin films reliably at high concentrations. One possible reason for the difficulties in p-doping ZnO could be because of self compensating doping mechanisms due to defects, a phenomenon seen in other II-VI materials. Therefore unlike GaN based devices, efficient long lifetime ZnO based LEDs and laser diodes may require low defect density homogeneous substrates. Recently we have been able to grow 1-3 mm^3 ZnMgO free nucleating crystals and several mm thick ZnMgO layers on ZnO substrates with uniform composition by the hydrothermal method. Up to five percent magnesium was incorporated into the ZnO lattice with a corresponding shift of up to 80 MeV in the near band edge photoluminescence. Photoluminescence performed on multiple samples from the same experiment showed uniform magnesium incorporation with only a 1-2 percent deviation in magnesium concentration. Details of growth conditions and characterization of the samples will be discussed. These initial results show the potential of using the hydrothermal technique to grow ZnO, ZnMgO alloys, and other ZnO based alloys to produce substrates with compositional uniformity for lattice matched transparent substrates and bandgap engineering.

11:15 AM EE8.11
ZnO-based p-n junctions with p-type ZnO by ZnTe oxidation.
Eliana Kaminska[1], Ewa Przezdziecka[2], Anna Piotrowska[1], Jacek Kossut[3], Pawel Jagodzinski[1], Krystyna Golaszewska[1], Elzbieta Dynowska[2], Witold Dobrowolski[2], Lukasz Klopotowski[2], Elzbieta Lusakowska[2] and Anna Wojcik-Jedlinska[1]; [1]Institute of Electron Technology, Warsaw, Poland; [2]Institute of Physics PAS, Warsaw, Poland; [3]Institute of Physics, PAS, and ERATO Semiconductor Spintronics, Warsaw, Poland.

The feasibility of p-type conductive ZnO has generated an enormous amount of interest over the past few years. Although improved, the acceptor doping of ZnO still remains an active area of research and development. In this communication we discuss preparation of p-type ZnO by oxidation of nitrogen-doped p-type zinc telluride and report on fabrication of ZnO p-n homojunctions. The starting ZnTe material was grown by MBE, in hydrogen-free atmosphere, either on GaAs or on bulk ZnTe. For oxidation, samples were furnace annealed in O_2 flow at 600°C. N-type ZnO was deposited by rf magnetron sputtering from ZnO target. Secondary ion mass spectrometry, x-ray diffraction and atomic force microscopy were used to examine the composition, microstructure and surface morphology of ZnO films. The transport properties of p- and n-type ZnO layers were assessed from Hall effect measurements. Photoluminescence spectra were measured with the excitation of 325nm line of He-Cd laser. Electrical characteristics of p-n junctions were obtained by conventional I-V measurements. The microstructure of p-type ZnO films was polycrystalline with inclusions of metallic Te, most probably due to the fact that sublimation of tellurium is inhibited in the course of the oxidation. The thickness of p- and n-type regions was 0.6 - 1 μm. Free carrier concentrations in p- and n-type ZnO were 0.1-1x$10^{18}$$cm^{-3}$ and about 1x$10^{18}$$cm^{-3}$, respectively. Through optimizing various critical fabrication steps, including development of ohmic contacts to p-type and to n-type ZnO and controlled chemical etching of ZnO, we achieved high quality rectifying p-n junctions. Part of the research was supported by grants from the European Commission NANOPHOS IST-2001-39112 within the 5th Framework Program and from the State Committee for Scientific Research PBZ-KBN-044/P03/2001. J. Kossut and E. Przezdziecka acknowledge the support from Foundation from Polish Science.

11:30 AM EE8.12
p-Type Nitrogen-Doped ZnO Thin Films Fabricated by

Pulsed Laser Ablation. Arnold Allenic[1], Zhendong Hu[2], Yong Che[2], Bing Liu[2], Wei Guo[1] and Xiaoqing Pan[1]; [1]Materials Science and Engineering, University of Michigan, Ann Arbor, Michigan; [2]Materials Research Group, IMRA, Inc., Ann Arbor, Michigan.

ZnO thin films were fabricated on (0001) sapphire substrates by pulsed laser ablation of mixed Zn_3N_2-ZnO and Zn-Zn_3N_2 targets. X-ray diffraction and cross-sectional transmission electron microscopy studies confirm the formation of epitaxial ZnO films. The nitrogen concentration determined by nuclear reaction analysis is in the range of 10^{21} cm^{-3}. X-ray photoelectron spectroscopy and low-temperature photoluminescence studies show the existence of hydrogen at the surface and in the films. The electrical transport properties were determined by Hall-effect measurements. As-deposited films are n-type ($\sim 10^{19}$ cm^{-3}) and have a small mobility possibly due to the presence of electrically inactive nitrogen-related defects. Long anneals in nitrogen result in semi-insulative and photoconductive ZnO. Rapid thermal annealing of the films results in p-type conductivity. Hall-measurements give an average resistivity of 850 Ω.cm, a mobility of 0.32 cm^2/V.s, and a hole concentration of 2.3 10^{16} cm^{-3}. The influence of Zn-rich growth conditions will be discussed. The dependence of the resistivity on the annealing temperature suggests that nitrogen acceptors are activated due to the dissociation of ZnNH complexes.

11:45 AM EE8.13
Epitaxially Grown Pulsed Laser Deposited $Mg_xZn_{1-x}O$ (0<x<1) Thin Films and Excitonic and Radiative - Non Radiative Recombination Kinetics. Shiva S. Hullavarad[1], S. Dhar[1], I. Takeuchi[1], T. Venkatesan[1], John Foreman[2], Henry Everitt[2,4] and R. D. Vispute[3]; [1]Center for Superconductivity Research, University of Maryland, College Park, Maryland; [2]Department of Physics, Duke University, Durham, North Carolina; [3]Bluewave Semiconductors, Columbia, Maryland; [4]Army Research Office, RTP, North Carolina.

ZnO and $Mg_xZn_{1-x}O$ have been subjects of intense scientific research as wide-band-gap optoelectronic materials. Their excellent material properties are promising for blue and UV photon emitters and detectors. ZnO and $Mg_xZn_{1-x}O$ also possess unique figures of merit, such as higher band gap energy tunable from - 3.3 to 7.8 eV, and free-exciton binding energy of 60 meV (much larger than that of GaN $\sim$26 meV) along with its larger absorption coefficient compared to GaN make ZnO and its alloys - the potential candidates for optoelectronics applications, such as blue and ultraviolet (UV) light emitters and UV detectors. The large exciton binding energy ensures that excitonic emission is prominent at room temperature. In this work we present results on the optical characterization of Pulse Laser Deposited epitaxially grown thin films of ZnO and $Mg_xZn_{1-x}O$ on sapphire. The crystalline quality and composition of alloys are characterized by X-Ray Diffraction and Rutherford Back Scattering (RBS) - ion channeling techniques respectively. The composition of the films is found to have strong dependence on the growth parameters. The photo generated carrier decay times are analyzed by time-resolved photoluminescence (TRPL) measurements. Since most optical and electrical devices are operated at room temperature, understanding the fundamental excess carrier recombination dynamics at 300 K is required to evaluate the relevant radiative and non-radiative recombination mechanisms and thus to improve the performance of devices. We have observed from initial TRPL measurements evidence of competing non-radiative relaxation processes and radiative recombination as a function of Mg concentration in the MgZnO samples. Particularly noteworthy is the observation of an extremely strong excitonic feature in the $Mg_xZn_{1-x}O$ (x=0.13) sample, whose decay characteristic was investigated with TRPL. Conclusions about the correlation between material quality and radiative recombination efficiency, obtained by comparing RBS and PL-TRPL measurements, will be discussed.

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

1:30 PM *EE9.1/FF18.1
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.

Invited Talk. 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 EE9.2/FF18.2
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 EE9.3/FF18.3
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 EE9.4/FF18.4

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 EE9.5/FF18.5

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 EE9.6/FF18.6

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 EE9.7/FF18.7

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 $\sim$60meV. Its bandgap of $\sim$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 EE9.8/FF18.8

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 EE9.9/FF18.9

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$\sim$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 EE10: Poster Session: Progress in Semiconductor Materials V - Zn0 and Dilute Nitrides
Wednesday Evening, November 30, 2005
8:00 PM
Exhibition Hall D (Hynes)

EE10.1

Growth of a-plane ZnO on r-plane sapphire by plasma-assisted MBE. J. Q. Xie[1], J. W. Dong[1], A. Osinsky[1], P. P. Chow[1], Y. W. Heo[2], D. P. Norton[2], S. J. Pearton[2], A. L. Cai[3], J. F. Muth[3], X. Y. Dong[4], C. Adelmann[4] and C. J. Palmstrom[4]; [1]SVT Associates, Eden Prairie, Minnesota; [2]Materials Science and Engineering, University of Florida, Gainesville, Florida; [3]Electrical and Computer Engineering, North Carolina State University, Raleigh, North Carolina; [4]Chemical Engineering and Materials Science, University of Minnesota, Minneapolis, Minnesota.

ZnO is a promising candidate for optoelectronic applications, such as UV/blue light emitting diodes and UV laser diodes. When grown on c-plane sapphire, analogous to III-nitride, the total polarization of ZnO is aligned along the [0001] growth direction and the polarization-induced fields may cause reduction in oscillator strength and a redshift of optical transitions in ZnO-based quantum wells. One way to eliminate the out-of-plane polarization effects is to grow the structures along non-polar directions, e.g., grow on r-plane sapphire. In this study, we report the epitaxial growth of ZnO thin films on r-plane sapphire by RF-plasma-assisted molecular beam epitaxy. X-ray diffraction studies indicate that the epitaxial relationship between ZnO and r-plane sapphire is $(11\text{-}20)_{ZnO}$ parallel to $(1\text{-}102)_{sapphire}$ and $[0001]_{ZnO}$ nearly parallel to $[\text{-}1101]_{sapphire}$. Atomic force microscopy measurements reveal islands extended along [-1101] direction of sapphire. The surface morphology might be correlated with surface terminated dislocations. X-ray omega rocking curves for the ZnO (11-20) reflection measured either parallel or perpendicular to the island direction suggest the dislocation density anisotropy along these directions. However, transmission electron microscopy measurements show little evidence for the presence of a significant density of misfit dislocations between the ZnO and the sapphire, which is quite different from previous reports. Ordinary and extraordinary indices of refraction of the a-plane ZnO film were measured using a prism coupling waveguide technique. The dispersion of the transverse electric (TE) and transverse magnetic(TM) refractive indices was studied systematically for a-plane ZnO grown on r-plane sapphire in the visible region. The refractive indices change periodically with an azimuthal angle with respect to the c-axis of the a-plane ZnO film for TE mode wave at wavelength of 632.8 nm while the refractive index of TM mode wave is a constant. This research was supported by Army contract #W911NF-05-C-0024, monitored by M. Gerhold. The authors also acknowledge partial support from AFOSR contracts #FA9559-04-C-0010 and # FA9550-04-C-0051, monitored by T. Steiner.

EE10.2

Non magnetic doping effect on the magneto-transport properties of Mn doped ZnO Dilute Magnetic Semiconductors. Govind Mundada, Srikanth Manchiraju, B. Robertson, T. Kehl, Kunal Paul and K. Ghosh; Physics,Astronamy and Materials Science, Missouri State University, Springfield, Missouri.

Dilute Magnetic Semiconductors (DMS) are a rare group of promising materials that utilize both electronic charge, a characteristic of semiconductor materials, and electronic spin, a characteristic of magnetic materials. This combination of charge and spin degrees of freedom in a single substance leads to a unique interplay of magnetic, optical, and electronic functionalities. Recently, DMS have received much attention due to their potential use in novel spintronic devices and quantum bits. Oxide based DMS show promise of ferromagnetism at room temperature.Zinc Oxide (ZnO), a short wavelength transparent opto-electronic material, is an interesting prospect for spintronics due to its unique magnetic, electrical, and optical properties. ZnO doped with a transition metal like manganese and non magnetic metals (Al,Cu) is a DMS which has strong exchange interaction between localized d electrons and sp band carriers. In this work, High quality thin films were deposited epitaxially on c plane of sapphire single crystals. Al and Cu doped ZnMnO films were prepared by pulse laser deposition (PLD) technique at 600^0C in 6e-5 Torr of oxygen. The effect of non magnetic doping on the structural and electro-magnetic properties of these films was studied using X-Ray Diffraction, Raman Spectroscopy, Atomic Force Microscopy,Scanning Electron Microscopy,and Magneto-Transport. X-Ray Diffraction confirms the epitaxial growth with a strong orientation along the c-axis, while Scanning Electron Microscopy reveals a single phase structure. Atomic Force Microscopy gives the RMS surface roughness

of the order of 1 to 2 nm over 5x5 μm^2. Raman spectrum confirms the Wurtzite structure of $Zn_{0.85}Mn_{0.15}O$. Magneto transport quantifies the Carrier concentrations and mobilities in $Zn_{0.85}Mn_{0.15}O$ and Al and Cu doped $(Zn_{0.80}A_{0.05})Mn_{0.15}O$ (A=Al and Cu) at room temperature. Carrier concentration for $Zn_{0.85}Mn_{0.15}O$ is 8.36e19 /cu.cm, where as for Al doped and Cu doped ZnMnO is increased to 3.93e20 and 4.97e20 respectively. Mobility for $Zn_{0.85}Mn_{0.15}O$ is 30.97 m^2/v-s, where as mobility for Al doped and Cu doped ZnMnO is decreased to 3.189 and 2.55 respectively. Detailed and interesting results were obtained from these studies would be shown in the presentation ahead.This work is supported by the National Science Foundation (award number DMR-0321187) and Research Corporation (award number CC6166).

EE10.3
Lowering of stimulated emission threshold of ZnO by electron doping. Yu-Guang Wang, Naoki Ohashi, Takamasa Ishigaki, Yoshiki Wada, Isao Sakaguchi and Hajime Haneda; Advanced Materials Laboratory, National Institute for Materials Science, Tsukuba, Ibaraki, Japan.

Owning to its large exciton binding energy, zinc oxide (ZnO) is know to be a potential material for light emitting devices, such as LEDs. For these applications, light emitting efficiency is absolutely important and, in particluar, lowering of its stimulated emission threshold is essential issue for lasing application of ZnO. In the present study, we investigated the effect of doping on the stimulated emission behavior of ZnO. We investigated two types of doped ZnO, i.e., hydrogen doped and aluminum doped ZnO. The samples were ZnO thin films deposited on sapphire or YSZ substrate with pulsed laser deposition. Thickness of the films were 50-70 nm. For hydrogen doping, hydrogen plasma irradiation was applied. We used inductively coupled plasma. The estimated hydrogen concentation in the films were in the order of 10^{18} cm^{-3}. Thermal diffusion technique was employed for Al-doping. The undoped ZnO films deposited on sapphire substrate was fired to enhance diffusion of Al in sapphire into ZnO films. Excitation intensity dependence of photoluminescence spectra revealed that excitation threshold for stimulated emission (P-band) reduced by these impurities. For hydrogen case, the thresphold for optically pumped stimulated emission of doped film was about 1/10 of that of the original film. For aluminum case, 1/5 reduction was confirmed. Looking at the result of Hall measurements, electron concentraiton in those films were more in the order of 10^{18} - 10^{19} cm^{-3}. This confirmes that hydrogen introduced by plasma irradiation as well as aluminum introduced by thermal diffusion cause formation of shallow donor states. Thus, the current results indicate that stimulated emission behavior has strong relationship with donor concentration. At the present stage, the doping effect on stimulated emission threshold is attributed to passivation of ionized defects formed in as-deposited films. We speculate that some sort of ionized defects act as non-radiative recombination center to reduce luminescence efficiency and such non-radiative centers were likely passivated by electrons injected by hydrogen or Al donors.

EE10.4
ZnO Light-Emission Array Fabricated into Nanometer Scale Pits on Silicon Substrate. Naoki Ohashi[1], Kazuyoshi Kobayashi[2], Hidetoshi Matsuda[2], Isao Sakaguchi[1], Takashi Sekiguchi[1], Hajime Haneda[1], Hirokazu Chazono[2] and Masayuki Fujimoto[3]; [1]Advanced Materials Laboratory, National Institute for Materials Science, Tsukuba, Ibaraki, Japan; [2]Taiyo Yuden Co., Ltd, Haruna-machi, Gunma, Japan; [3]Graduate School of Electronic Science and Technology, Shizuoka University, Hamamatsu, Shizuoka, Japan.

ZnO is well-known phosphor material with blue-green light emission and is widely applied to vacuum fluorescence display (VFD) and field emission display (FED) panels because of higr emission efficiency under low energy electron irradiation, e.g., 20 eV. On the other hand, patterning of light emitting elements is also critical importance; however, conventional patterning methods of ZnO phosphor for VFDs are restricted to screen-printing. The use of relatively large phosphor grain is likely one of the causes of the limitation of image resolution in VFDs and FEDs, because micro-fabrication technology for silicon based materials enabled high density integration of micro-electron-emitter arrays. To obtain high resolution of ZnO phosphor pattern, the effort of direct patterning of ZnO using self-assembled mono-layer (SAM) was actively pursued before. However, luminescence properties of the pattered ZnO deposited from aqueous solution is a little poor for practical applications and additional thermal treatments are necessary to improve luminescence efficiency. In the present work, we tried and succeeded to fabricate nano-meter-order ZnO light emission arrays on Si substrate using chemical mechanical planarization (CMP) and metalorganic chemical vapor deposition (MOCVD) which are indispensable technologies of multi level metallization of CMOS. Array of square pyramidal pits surrounded by {111}Si plane on (100)Si substrate was formed by a selective etching technique using a mask pattern prepared with photo-lithography. As a result, an wafer with square pyramidal pits (1 $\mu m \times 1$ μm and 1.7 $\mu m \times 1.7$ μm) was obtained, and this wafer was used as a substrate for ZnO thin-film deposition. ZnO thin film was grown from of zinc acetylacetonate monohydrate (CH3COCHCOCH3)2ZnEH2O as a source material with Ar carrier gas at deposition temperature of 600oC on the substrate using an electron cyclotron resonance (ECR) plasma assisted MOCVD. The ZnO thin-film deposited substrate was polished with Al2O3 powder and 0.1 mol% of HCl solution using CMP. The top surface of ZnO film was removed and the ZnO deposited into the pits was remained. The appropriating polishing depth gave smaller pits filled with ZnO. Finally 800 nm X 800nm and 250nm X 250nm of square shape of pits array of ZnO were obtained. Each ZnO pit showed only the excitonic band-edge luminescence. This indicates that CMP process did not introduce active defects causing defect related visible luminescence, although mechanical damage is one of the most critical problem causing degradation of ZnO luminescence. Namely, the present results indicates that CMP process applied in this study is appropriate for machining of ZnO for optical applications. It was clearly illustrated that micro-meter scaled and nano-meter scaled ZnO filled pits both emitted band-edge luminescence quite well.

EE10.5
Zinc oxide quantum dots embedded films by metal organic chemical vapor deposition. S. T. Tan[1,2], X. W. Sun[1], X. H. Zhang[2], B. J. Chen[1] and S. J. Chua[2]; [1]Electrical & Electronic Engineering, Nanyang Technological University, Singapore, Singapore; [2]Institute of Materials Research and Engineering, Singapore, Singapore.

The ZnO quantum dots (QDs) were grown on Si (100) by MOCVD. The growth temperature was set at 350°C. DimethylZinc (DMZn), N_2 gas and high-purity O_2 were used as the zinc source, carrier gas and oxidizing agent, respectively. The flow rates of DMZn and O_2 were set at 20 sccm each for the QDs fabrication. The DMZn bubbler was kept at -10°C in a coolant water bath. For comparison purpose, a highly c-axis oriented ZnO thin film was grown at 350°C with the flow rate of DMZn and O_2 maintained at 3 sccm each. The ZnO films were characterized by X-ray diffraction (XRD), high-resolution transmission electron microscopy (HRTEM), and photoluminescence (PL) excited with a 325 nm line He-Cd laser of 30 mW at a temperature of 80 K. From the XRD measurement, the ZnO film grown with DMZn and O_2 at a flow rate of 3 sccm each exhibits highly c-axis oriented structures. The crystallinity of QDs embedded film was poor and exhibits polycrystalline structures with the existence of various crystallographic planes. By using Scherrer's formula, the grain size corresponding to crystallographic plane (100), (002), and (101) was estimated to be 3.45, 9.92, and 4.83 nm, respectively. The HRTEM images of the ZnO QDs embedded film show clearly that the ZnO QDs were uniformly distributed in the film and the size of the QDs measured was in the range of 3 to 12 nm. The QDs size was plotted as histogram and the distribution can be well fitted with the Gaussian distribution. Most QDs were distributed at around 7 nm in diameter. The PL of the highly c-axis oriented and QDs embedded ZnO thin film were measured at temperature 80 K. The PL spectrum of the highly c-axis oriented ZnO film is dominated by the near-band-edge emission (NBE) at 3.356 eV, which is attributed to the neutral donor-bound exciton (D^0X). The spectrum, however, shows drastic difference for QDs embedded film. The emission spectrum of the QDs embedded film measured at 80 K shows a broad NBE with a tail up to 3.6 eV and peaking at around 3.358 eV, which is attributed to D^0X. Comparing the PL of QDs embedded film measured at 80 K and room temperature, there is an obvious change in the NBE shape. At temperature of 80 K, the emission peaks at 3.358 eV (D^0X) and 3.509 eV can be identified even with the presence of the interference noise. The quantum confinement effect of the band tail emission could be observed from PL measurement. Using the equation that governs the QDs band gap energy and size, the QDs band gap of the dot size of 3 to 12 nm was calculated to be 4.130 to 3.425 eV, respectively. Due to the presence of smaller percentage of 3 nm QDs, their contribution to the emission is weak. Hence, its corresponding emission could not be observed in the PL measurement. Meanwhile, for the most distributed QDs with diameter of 7 nm, the corresponding emission calculated was 3.503 eV. The emission peak 3.509 eV in 80 K PL measurement is then due to the quantum confinement ZnO QDs.

EE10.6
Laser Assisted Molecular Beam Deposition of High Mobility Zinc Oxide. Meiya Li[1], Nehal Chokshi[2], Robert L. DeLeon[2], Gary Tompa[2] and Wayne A. Anderson[1]; [1]Electrical Engineering, SUNY at Buffalo, Buffalo, New York; [2]AMBP Tech Corporation, Tonawanda, New York.

Laser Assisted Molecular Beam Deposition (LAMBD) enables the deposition of a wide variety of materials at room temperature, making it a promising technique to deposit various critical layers for flexible

displays and other applications utilizing flexible substrates. We have utilized LAMBD to deposit Zinc Oxide (ZnO), a II-VI semiconductor material, at room temperature. The production of ZnO films via LAMBD utilizes an excimer laser induced ablation plume of zinc in combination with pulsed oxygen gases to create a molecular beam of ZnO clusters. The deposited films have been characterized structurally and electrically in an as deposited state as well as after post deposition excimer laser annealing. The films undergo a clear structural change from a nanoparticle like film to either a microgranular film or smooth continuous film depending upon the laser annealing powers. The thickness and refractive index of these thin films were defined using ellipsometry, with values ranging from 99 to 230 nm, and 1.21 to 1.66, respectively. Films tested after laser-annealing have smaller values of refractive index when compared with as-deposited films. The scanning electron microscopy (SEM) images confirmed the thicknesses, gave surface morphology and indicated a difference in morphology when comparing laser-annealed and as-deposited films. Al ohmic contacts were made to both as-deposited and laser-annealed ZnO thin films. The specific contact resistance between 1.3 cm spaced contacts on Hall bars was determined to be 39.4 kohm for the as-deposited contact, 6.52 kohm for the contact annealed in air at 400 °C, and 3.52 kohm for the contact annealed in air at 600 °C. However, a non-linear behavior was exhibited in both as-deposited and 400 °C-annealed contacts. Resistances for both 400 °C-annealed and 600 °C-annealed contacts were reduced at least one order of magnitude compared to the as-deposited contact. Contacts annealed at 600 °C showed a linear ohmic behavior and resistance slightly improved compared to the contact annealed at 400 °C. Annealing in air gave a lower resistance compared with forming gas anneal. Photoconductive behavior was clearly seen on the laser-annealed samples. The values of conductivity (ΔG) due to 100 mW/cm^2 solar-simulated light were calculated to be 2.8 x 10^{-4} ohm^{-1} and 3.04 x 10^{-5} ohm^{-1} for laser-annealed samples under air ambient and forming gas treatments, respectively. Additionally, the carrier concentration and Hall effect mobility of both as-annealed and laser-annealed samples were measured at room temperature. For one set of samples, the carrier concentration and Hall mobility were 1.68 x 10^{15} cm^{-3} and 10.6 cm^{2}V^{-1}s^{-1} for the as-deposited film; 1.12 x 10^{15} cm^{-3} and 21.9 cm^{2}V^{-1}s^{-1} for the laser-annealed film, respectively. ZnO films deposited and laser-annealed under other conditions gave a Hall mobility value up to 244 cm^{2}V^{-1}s^{-1}. Auger electron spectrscopy (AES) data will also be reported.

EE10.7

Substrate Variation effect on electrical and magnetic properties of Mn doped ZnO with different thickness of Dilute Magnetic Semiconductors. Srikanth Manchiraju, Govind Mundada, T. Kehl, B. Robertson, Kunal Paul and K. Ghosh; Physics, Astronomy and Materials Science, Missouri State University, Springfield, Missouri.

Diluted magnetic semiconductors are semiconductors doped with ions that have a net spin. These type of materials have a lattice structure similar to that of the undoped semiconductors, at least for the diluted magnetic case. Potential applications are in the field of spin-dependent semiconductor electronics and optoelectronics, or so-called spintronics and optospintronics. ZnO and TiO_2 doped with 3d-magnetic atoms have been studied because of interesting magnetic behavior despite the fact that the origin of magnetic behavior is not clearly understood. Pulsed laser deposition (PLD), a versatile technique to realize epitaxial/highly oriented thin films of oxide electronic materials would be used to develop good quality thin films. The degree of film densification and size of specific defects (i.e. pores, grain boundaries, cavities, etc.) is strongly dependent on the processing temperature and particular substrate. The substrate material can influence the kinetics of film growth having different thermal conductivity, specific heat and emissivity. Its selection is significant for growth of thin films because matching in lattice parameters and crystal structure between the film and substrate strongly affects the crystal growth behavior of the film. Epitaxial films were produced with the thickness varying between 50 and 250nm on Silicon and Sapphire substrates, by means of the pulse laser deposition technique and under the equivalent epitaxial growth conditions. Substrate temperature of 600C, Oxygen atmosphere and pressure of the order 1e-5 were maintained during growth. The effect of substrate on the microstructure and magneto-transport of epitaxial $Zn_{0.8}Mn_{0.15}O$ thin films have been investigated. Structural, Surface, Magnetic and Optical properties have been observed on both Silcon and Sapphire substrates with different thickness using X-Ray difraction, AFM, SEM, Magneto-transport and, Raman spectroscopy. X-Ray Diffraction shows that films are highly epitaxial and c-axis oriented. It confirms the wurtzite structure without any impurity phase. AFM images shows that film surface is smooth with RMS roughness of the order of 1-2nm over 5x5μm^2. SEM images confirms films of single phase. Raman Spectroscopy also confirms the epitaxial nature of the films on various substrates. Magneto-transport properties have also been investigated which includes carrier concentration and mobility. Carrier concentration of film on Si is 2.4e19/cm^3 increased to 8.36e19/cm^3 by changing to sapphire. Similarly, mobility decreased in sapphire to a value of 30.97 from 107.59 m^2/(v-sec). in Silicon by substrate change. Other substrate variation studies being investigated were glass and quartz. Detailed results on various substratess will be presented in the paper.This work is supported by the National Science Foundation (award number DMR-0321187) and Research Corporation (award number CC6166).

EE10.8

Czochralski Crystal Growth of Zinc Oxide-Tellurium Oxide System. Jalal M. Nawash[1] and Kelvin G. Lynn[2]; [1]Center for Materials Research, Washington State University, Pullman, Washington; [2]Center for Materials Research, Washington State University, Pullman, Washington.

Czochralski (CZ) technique was employed in an attempt to grow a single crystal of the system ZnO-TeO_2. The grown crystal has a high resistivity of the order 10^{13} ohm-cm. A good quality grown crystal is expected to be transparent with a light brown color. The optical band gap will be presented. Different mole percentages have been tested for growth. The mole percentages that have been tried are: ZnO:TeO_2 (21%:79%, 35.5%:64.5%, 40%:60%, 50%:50%). These mole percentages will be shown to have a melting point below 850° C. At the beginning of the research, no phase diagram was available for this material. No one has reported the growth of a single crystal of this material using CZ technique or any other method. Powder X-Ray Diffraction of the resultant material shows that 40%:60% has a monoclinic crystal structure with the lattice constants of 12.7 Å, 5.2 Å , and 11.8 Å, and the angles of 90°x99.6°x90°. The 50%:50% has the orthorhombic crystal structure, with the lattice constants of 7.3 Å, 6.4 Å, and 12.3 Å. Several attempts were performed to pull a single crystal. It was found that the best mole percentage is 35.5%:64.5%. The pulled material grows in a uniform pattern, such that necking and conning are noticed. Single crystals were isolated and studied, each one of them were transparent. Some of them were colorless, while some appeared dark green or brown. In the crystals that seem brown, the Scanning Electron Microprobe shows that they are of the same phase as the colorless ones, but internal fractures in the colorless ones cause them to appear brown. Some electrical measurement results of these single crystals will be presented. Other mole percentages tend to form phases. As an example: 40%:60%- ZnO:TeO_2 tends to form four different phases during the growth. Two are major ($Zn_2Te_3O_8$, $ZnTeO_3$), and two are minor ($ZnTe_5O_{11}$, Zn_3TeO_6). In fact, in the last phase, Te has a valance number of 6. This material is very rare and has never been reported in literature. A glass was also made out of the 35.5%:64.5% mole percentage. The conditions to make glass from this material were established, such that if the cooling rate was fast (1K/min-10K/sec), glass will form instead of a crystalline material. The color of the resultant glass is yellow. This type of glass is of exceptional significance. With a high refractive index between 2 and 2.5 in addition to its high transmissivity, and a low glass transition temperature around 328° C. This makes the glass a perfect candidate for manufacturing fiber optics. Some transmission and absorption tests were also conducted on the glass. We would like to thank the support from the: Space Missile Defense Command (SMDC), Contract Number: DASG60-02-C-0084

EE10.9

Investigation of Optical and Electrical Properties of Co-Doped ZnO Thin Films. Kousik Samanta, Pijush Bhattacharya and Ram S. Katiyar; Physics, Univ. of Puerto Rico, San Juan, Puerto Rico.

Thin films of Co doped ZnO have been extensively studied for high Curie temperature dilute magnetic semiconductor (DMS) after theoretical predictions. However, the experimental reports have not clearly demonstrated that the observed ferromagnetism is from the uniformly doped or some segregated secondary phases. In this work, we have studied in detail of its optical and electrical properties with Co doping (1-20%) in ceramic and thin film forms in order to understand the effect of Co doping and to identify the secondary phases. $Zn_{1-x}Co_xO$ thin films were grown on Al_2O_3 (0002) substrates by pulsed laser deposition technique. The ceramic targets were prepared by the mixing of ZnO and Co_3O_4 powders with stoichiometric amounts (x = 0.01, 0.05, 0.10, 0.15 & 0.20) and using standard ceramic processing. PL spectra of $Zn_{1-x}Co_xO$ ceramic and thin films were carried out in the temperature range 77K to 300K using UV 351nm exciting radiation from an Ar^+ laser. Free excitonic and bound excitonic peaks are clearly observed at 77K at both $Zn_{1-x}Co_xO$ ceramics and thin films. In the case of Co doped ZnO ceramics the free excitonic peak shifted by ~7meV from the undoped ZnO. Although in the thin films band gap of $Zn_{1-x}Co_xO$ was decreased from 3.2 to 2.8 eV, there was no appreciable shift of the free excitonic peak observed in the PL of thin films. The resistivity of ZnO thin films increased and the mobility decreased with the increase of

Co concentration. Temperature variation of PL and detailed electrical characterization in correlation with Co concentration will be presented. The authors acknowledge partial financial supports from DE-FG-02-01ER45868 and NASA#NCC3-1034 and DAAD 19-03-1-0084 grants.

EE10.10
Structural and Spectroscopic Studies of ZnO and GaN Powders Calcined with Transition Metal Oxides. Lori Noice[1], Bjoern Seipel[1], Chunfei Li[1], Amita Gupta[2,1], Peter Moeck[1], Rolf Erni[3], Nigel D. Browning[3,4], Frank Owens[5] and K. V. Rao[2]; [1]Department of Physics, Portland State University, Portland, Oregon; [2]Department of Materials Science, The Royal Institute of Technology, Stockholm, Sweden; [3]Department of Chemical Engineering and Materials Science, University of California at Davis, Davis, California; [4]National Center for Electron Microscopy, Lawrence Berkeley National Laboratory, Berkeley, California; [5]Department of Physics, Hunter College, City University of New York, New York, New York.

Researches at Portland State University, the National Center for Electron Microscopy (at the Lawrence Berkeley National Laboratory), Hunter College New York, and The Royal Institute of Technology collaborate on the development and characterization of dilute magnetic semiconductors for potential spintronics applications. After the theoretical prediction that wide band-gap semiconductors may attain Curie temperatures well above room temperature when doped with transition metals (Dietl T., Ohno H., Matsukura F., Cibert J., and Ferrand D. Science 287 (2000) 1019), ferromagnetism above room temperature was reported for zinc oxide doped with manganese (Sharma P., Gupta A., Rao K.V., Owens F., Sharma R., Ahuja R., Guillen J., Johansson B., and Gehring G. Nature Materials 2 (2003) 673). Additional doping with copper is by several authors considered beneficial to support magnetic coupling by introducing holes. At Portland State University, calcined powders of zinc oxide that originally contained a few percent manganese dioxide and copper oxide were analyzed using qualitative and quantitative powder X-ray diffraction. The results suggest incorporation of manganese and copper into the zinc oxide lattice with corresponding shifts in the semiconductor's lattice constants. Calcined powders of gallium nitride that originally contained a few percent copper oxide where analyzed using energy dispersive x-ray spectroscopy (EDXS), electron energy loss spectroscopy (EELS - at the National Center for Electron Microscopy), transmission electron microscopy, and quantitative (Rietveld) powder X-ray diffraction. Shifts in the semiconductor's lattice constants were detected by the application of the Rietfeld method. This supports the conclusion of copper incorporation into the gallium nitride lattice. Consistent with the Rietveld analysis, EELS indicated expansions in the c-axis direction. EDXS, on the other hand, proved the incorporation of copper into the gallium nitride lattice. Although not a constituent of the precursors of any calcined sample, copper dioxide was found in all the gallium nitride powders but not in the zinc oxide powders.

EE10.11
Time resolved photoluminescence study of ZnO nanorods grown on GaN by using hydrothermal synthesis.
Quang Le Hong, National University of Singapore, Singapore, Singapore.

Well-aligned ZnO nanorods with diameter 100nm and height 2um grown on GaN were fabricated by using hydrothermal sysnthesis at low temperature 100C.The time resoleved PL measurement at free exciton peak were carried out to characterize the optical quality of the ZnO nanorods. The decay profiles were single exponential form and the decay constants of 84ns was obtained using a least square fit of the data.In addition,the time resolved measurements had been performed at different excitation powers and at different temperatures, from 4K to room temperature.With increase of the pump power, the transition from exciton stimulated emission to the electron hole plasma regime can be clearly observed. By varying the temperature from 4K to 300K, the measured decay time decreased accordingly. We found that the nonradiative recombination process play an important role and dominate the decay of exciton population at high temperature.This process depends on the density of defects and impurities of the ZnO nanorods.

EE10.12
Effect of substrate temperature, ion implantation and annealing studies of ZnO films prepared by Pulsed Laser Deposition. Selvaraj Venkataraj, Haruki Royken, Isao Sakaguchi, Naoki Ohashi and Hajime Haneda; Electroceramics group, Advanced Materials Laboratory, National Institute for Materials Science, 1-1 Namiki, Tsukuba, Ibaraki, Japan.

Zinc oxide (ZnO), is one of the II-VI semiconductors with excellent structural, optical and electrical properties, finds numerous applications in modern technology and has recently attracted considerable attention. High quality ZnO thin films have been prepared by pulsed laser deposition (PLD) technique on sapphire substrates for different substrate temperatures. The structural and optical properties of ZnO films were investigated in terms of deposition conditions, such as substrate temperature, ion implantation and post growth annealing. The film properties have been studied using different techniques such as X-ray diffraction (XRD), Atomic force microscopy (AFM), Photoluminescence (PL), Raman and optical spectroscopy. The X-ray diffraction measurement reveals that the films are highly textured in c-axis and the quality of the texture improves with the increasing substrate temperature. Both rocking curve and AFM measurement show grain growth as the substrate temperature increases. The room temperature PL spectra shows strong peak near the band edge at 380 nm and a very weak green emission centred at 600 nm, which is attributed to the oxygen vacancies. The characteristic Raman vibrational modes prove the hexagonal (wurtzite) crystal structure of ZnO which is also evidenced from XRD measurements. From the optical spectroscopic measurements, it has been observed that the film possesses nearly 80% transparency in the visible region with a band gap value of $\sim$3.15eV. The present study reveals that the ZnO films synthesized by PLD express fairly good optical properties and low defect density as well as excellent crystallinity. The transition metal ion implantation and post growth annealing studies are in progress and the results will be presented in the conference.

EE10.13
Roles of Laser-Ablation of Mn in Initial Stage of Growth of ZnO Nanorods by Chemical Vapor Deposition. Takashi Hirate, Hiroshi Miyashita, Takashi Kimpara, Kazumoto Takizawa and Tomomasa Satoh; Faculty of Engineering, Kanagawa University, Yokohama, Japan.

ZnO is an attractive II-VI compound semiconductor material for various optoelectronic devices due to its wide band gap of 3.37 eV at room temperature and its large excitonic binding energy of about 60 meV. Recently, growth of various nano-structures of ZnO such as nanorod, nanobelt, nanowall, etc. has been reported. A report on initial stage of growth of these ZnO nanostructures, however, is few. We have studied on fabrication of ZnO nanorods by a low-pressure thermal chemical vapor deposition (CVD) method cooperated with a laser ablation of Mn, and found that the laser ablation has drastic effects on morphology of ZnO nanorods. In this paper, we studied on an effect of laser ablation of Mn at an initial stage of growth of ZnO nanorods. The fabrication method is almost same method used in our previous study. Metal Zn vapor and O2 gas are used as precursors to synthesize ZnO, and N2 is used as carrier gas. A metal Mn pellet is placed near a Si(111) substrate in a deposition chamber and ablated by a pulsed Nd:YAG laser beam (wavelength =1.064 mm, pulse width = 8 ns, repetition frequency = 10 shots/sec). When the laser ablation is not used, randomly oriented ZnO nano-whiskers are only grown and well-oriented ZnO nanorods are not grown. The growth conditions are as follows. O2 flow rate is 1.5 sccm. The growth temperature is 550 C. The growth pressure is 27 Pa. The laser energy is 0.31 J/shot/ mm2 and the laser-irradiated area on the sintered ZnO pellet is 0.13 mm2. Laser ablation and CVD are simultaneously started at t=0, and only laser ablation is stopped at t=tABL. CVD is continued since then and terminated at t=tCVD. We studied on the case of tABL=30 sec, 1 min and 3 min, and tCVD=30 sec, 1 min, 3 min and 15 min, satisfying tABL <= tCVD. When tABL = tCVD, i.e., both laser ablation and CVD are also simultaneously stopped, experimental results are as follows. In the case of tABL = tCVD= 30 sec, a very thin columnar ZnO layer is formed. This layer is continuously formed on a Si(111) substrate and is very different from that formed by CVD without laser ablation where very fine discrete islands are formed with low number density. Both the thickness of this layer and the size of each columnar grain become larger with increasing tABL (= tCVD). When tABL = tCVD = 3 min, an initiation of growth of ZnO nanorods is observed on the continuous layer of 280 nm thickness. We conclude considering also the other experimental results that the laser ablation of Mn play a role of formation of a columnar grain layer of ZnO in advance of nanorods? growth. Once this layer formed, a ZnO nanorod is grown on each grain by CVD even if a laser ablation is not performed. When the laser ablation is performed for long time, the grain size become larger and the growth of nanorods is suppressed for some time period. Thus we can control the size and number density of ZnO nanorods by the laser ablation time tABL

EE10.14
Concentration and Defect Dependent Ferromagnetism Above Room Temperature in CO Doped ZnO Films Prepared by Metalorganic Decomposition. P. Kharel[1], Vaman M. Naik[2], Gavin Lawes[1], R. Suryanarayanan[1,3] and Ratna Naik[1]; [1]Department of Physics and Astronomy, Wayne State University, Detroit, Michigan; [2]Department of Natural Sciences, U Michigan-Dearborn, Dearborn, Michigan; [3]Permanent address: LPCES, Universite Paris-Sud, 91405, Orsay, France.

Research on inducing ferromagnetism at 300 K in semiconductor oxide materials is rapidly expanding because of their potential applications to spintronics. In particular, semiconducting oxides such as TiO_2 and ZnO doped with Mn, Co and Fe are expected to be ferromagnetic above room temperature.[1] Recently, we have successfully used a simple non-vacuum based spin-coating technique to prepare thin films of anatase and rutile TiO_2-doped with Co and Fe that were ferromagnetic at 300 K.[2] Here, we report on the preparation, XRD, EDX, Raman spectra and magnetization of thin films of $Zn_{1-x}Co_xO$ (x = 0, 0. 03, 0.05, 0.10, 0.20) spin-coated on sapphire substrates using a mixture of the metal-organic precursors Zn-ethylhexanoate and Co-ethylhexanoate in proper proportions. The thickness of the films ranged between 0.5 to 1 μm. The samples were annealed in air at 550 C. These samples show Raman signatures corresponding to wurtzite ZnO. Magnetization studies on these samples did not reveal any ferromagnetic order at 300 K. The samples with x = 0.03 were then heat treated in vacuum at T_v = 500 and 600 C. Only the samples that were heat treated at 600 C showed clear hysteresis loops at 300 K indicating the crucial role played by Tv. We further observed that ferromagnetism (FM) appeared only for a limited range of Co concentration, 0.03 < x < 0.10 (after heat treating at 600 C). Our data seem to suggest that the appearance of FM is dictated by both the oxygen defects and the critical concentration of Co and thus may lend support to a recent model proposed by Coey et al.[3] [1]For a recent review, see, T. Fukumura et al., Semicond. Sci. Technol. 20 (2005) S103 [2]R. Suryanarayanan et al., J. Phys. Cond. Matter 17 (2005) 755; Solid State Comm. 133 (2005) 439 [3]J. M. D. Coey et al., Nature Materials 4 (2005) 173

EE10.15
Nitrogen doping of ZnO films by nuclear transmutation.
Patrick Wellnius[1], John Muth[1], Anuj Dhawan[1], Jack Price[2] and Noel Guardala[2]; [1]ECE Dept, North Carolina State University, Raleigh, North Carolina; [2]Ion-Beam Materials Physics Group, Naval Surface Warfare Center, West Bethesda, Maryland.

P-type doping of ZnO remains a challenging task with nitrogen one canidate dopant. In this study, single crystal ZnO films are grown by pulsed laser deposition and ion beam processing is used to directly transmutate oxygen into nitrogen. Analytical ion beam techniques were used to monitor the transmutation process, and changes in film characteristics were monitored by making resistance, photoconductivity and photoluminescence measurements before and after ion beam processing. Post annealing steps were also explored as a means to reduce ion beam damage.

EE10.16
Indium, Gallium, and Aluminum Doping in Hydrothermal ZnO bulk crystals for Conducting Substrates.
Michael Callahan[1], Buguo Wang[2], Lioniel Bouthillette[1], Michael Suscavage[1] and Sheng-Qi Wang[2]; [1]SNHC, Air Force Research Lab, Hanscom AFB, Massachusetts; [2]Solid State Scientific Corporation, Nashua, New Hampshire.

ZnO based LEDs and laser diodes have not been demonstrated because of the inability to obtain p-doped ZnO thin films reliably at high concentrations. One possible reason for the difficulties in p-doping ZnO could be because of self compensating doping mechanisms due to defects, a phenomenon seen in other II-VI materials. Therefore unlike GaN based devices, efficient long lifetime ZnO based LEDs and laser diodes may require low defect density homogeneous substrates. Hydrothermal ZnO substrates offer a lost cost production method of producing large area ZnO substrates but generally have low conductivity. Therefore, a methodology is needed to produce low-cost, large-area conducting ZnO substates. A series of experiments were performed to intentionally dope hydrothermal ZnO with Ga, Al, and In to obtain low defect ZnO substrates with high conductivity. Changes in growth morphology due to the high levels of the group III dopants will be discussed. Photoluminescence, Hall , High Resolution X-ray, and Atomic Force Microscopy data will be presented along with dopant and impuritiy incorporation in the ZnO crystals.

EE10.17
Time-resolved Biexciton Behaviors in a ZnO Thin Film.
Fang-Yi Jen[1], Yen-Cheng Lu[1], Cheng-Yen Chen[1], Hsiang-Chen Wang[1], Chih-Chung Yang[1], Bao-ping Zhang[2] and Yusaburo Segawa[2]; [1]Institute of Electro-Optical Eng., National Taiwan University, Taipei, Taiwan; [2]Photodynamics Research Center, the Institute of Physical and Chemical Research, Sendai, Japan.

Because of its large exciton binding energy at about 60 meV, ZnO has attracted much attention in crystal growth and optical property characterization. With such a large exciton binding energy, the dominance of exciton recombination in the radiative process, even up to the room temperature, results in the high photon emission efficiency. Normally, in photoluminescence (PL) measurement with low excitation, the emission of donor-bound exciton (D0X) dominates the spectrum at low temperatures (< 60 K) and that of free exciton (FX) dominates at high temperatures. In the case of high excitation, the biexciton (XX) feature can be observed in a high-quality ZnO sample. Although the biexciton dynamics in other structures, as mentioned above, were widely studied, that in ZnO has not been well explored. In particular, the interplay between XX, D0X, and FX in ZnO has never been investigated. In this paper, we study the ultrafast biexciton dynamics in a ZnO thin-film sample with time-resolved photoluminescence (TRPL) measurement. In the measurement, not only the emission line (the M line) of XX is observed, but also that (the D0M line) of donor-bound biexciton (D0XX) can be clearly seen. The calibrated two-stage decay times are used to build the model of ultrafast biexciton dynamics in such a ZnO sample. The ZnO thin film was grown with MOCVD on (0001) sapphire substrate with 6 Torr in pressure at 450^{circ}C for 90 min. The TRPL intensity profiles reveal the formation sequence of various types of exciton. After FXs are first generated, part of them is trapped by neutral donors to form D0Xs. The other part contributes to the generation of XXs through FX scattering. Next, a donor-bound biexciton is generated through the trapping of a XX or two FXs by a neutral donor or the trapping of a FX by a D0X. Except D0X, the relaxations of all other exciton states show two decay stages. Either the increasing or decreasing trends of the calibrated decay times in increasing the excitation power are well interpreted with a four-level model.

EE10.18
Temperature-dependent Exciton Dynamics in a ZnO Thin Film. Yen-Cheng Lu[1], Fang-Yi Jen[1], Cheng-Yen Chen[1], Hsiang-Chen Wang[1], Chih-Chung Yang[1], Bao-ping Zhang[2] and Yusaburo Segawa[2]; [1]Institute of Electro-Optical Eng., National Taiwan University, Taipei, Taiwan; [2]Photodynamics Research Center, The Institute of Physical and Chemical Research, Sendai, Japan.

Temperature-dependent exciton dynamics has been an interesting issue in understanding the basic optical properties of semiconductors. Theories and experiments based on GaAs have shown that the free exciton radiative lifetime is related to the photoluminescence (PL) spectral width in varying temperature. Here, the finite PL spectral width of free exciton at non-zero temperatures is due to the kinetic energy distribution of exciton and hence is expected to increase with temperature. With such a kinetic energy or momentum distribution, the exciton recombination extends from zero momentum of the center of mass to a finite range. In this situation, the originally centralized oscillator strength is shared (and hence reduced) by this range of energy. Therefore, the radiative lifetime of a free exciton (FX) increases with temperature. Although such temperature dependencies have been studied in other materials, those in ZnO are still not well understood yet. Particularly, because of the abundance of donor-bound exciton (D0X) in ZnO and the shallow nature of such a donor (binding energy only 8-10 meV), FX and D0X are usually mixed in photon emission, particularly when the temperature is above 80 K. In this research, we investigate the temperature-dependent exciton dynamics by calibrating their decay times based on time-resolved photoluminescence (TRPL) measurements. The ZnO thin film was grown with MOCVD on (0001) sapphire substrate with 6 Torr in pressure at 450^{circ}C for 90 min. We measured the temperature-dependent photoluminescence (PL) decay time of the mixed system of FX and D0X in a ZnO thin film. From the measured cw PL spectra, we also calibrated the spectral widths of FX and D0X and the integrated PL intensity of the mixed system by fitting the related spectral part with two Gaussian functions. The radiative lifetime of the mixed system was then calibrated based on the thermal quenching rate of the integrated PL intensity of the system. With the radiative lifetime data, the FX radiative lifetimes were estimated by using a theoretical relation between the lifetime and the spectral width. From the results of FX radiative lifetime, we could calibrate the D0X radiative lifetimes. The results support our model that the D0X radiative behavior is similar to that of FX when the thermal energy is smaller than the donor binding energy.

EE10.19
Comparisons of Nano-material and Optical Characteristics of ZnO Grown on GaN and Sapphire. Wen-Yu Shiao[1], Chun-Yung Chi[1], Shu-Cheng Chin[1], Chi-Feng Huang[1], Tsung-Yi Tang[1], Yu-Li Lin[1], Lin Hong[1], Chih-Chung Yang[1], Bao-ping Zhang[2] and Yusaburo Segawa[2]; [1]Institute of Electro-Optical Eng., National Taiwan University, Taipei, Taiwan; [2]Photodynamics Research Center, the Institute of Physical and Chemical Research, Sendai, Japan.

The immature developments of p-type ZnO and ZnO-related ternary or quaternary compounds drive the need of the hybrid growth of ZnO and GaN. This idea is particularly interesting because of the small lattice mismatch between ZnO and GaN. Although the hybrid growth of ZnO with p-type GaN has led to the implementation of light-emitting devices, the material and optical properties of ZnO on

GaN have not been well studied yet. In this research, we investigate the differences of nanostructure and optical property of ZnO thin film between the samples grown on GaN and on sapphire. In material analysis, based on the technique of high-resolution transmission electron microscopy, we particularly pay attention to the interface structures between ZnO and GaN or sapphire. It is found that with a relatively higher growth temperature (450^{circ}C), the 30o basal plane orientation twist of ZnO with respective to its underlying layer (sapphire) in the case of on-sapphire growth was not observed in ZnO grown on GaN. This observation is confirmed with the measurement of X-ray diffraction. Although both cases lead to domain structures in spiral mode growth, the near-interface structures are quite different. In contrast to the growth on sapphire, the atomic arrangements at the interface between ZnO and GaN are quite well aligned. When the growth temperature is reduced to 200^{circ}C, although both cases lead to unclear domain structures, ZnO on GaN shows better crystalline quality either near the interface or near the surface. In optical study, the photoluminescence (PL) measurements show that with the high temperature growth, ZnO samples on GaN and sapphire have similar temperature-dependent behaviors. The thermal quenching behaviors of the integrated PL intensity, which represents non-radiative recombination strength, of the two cases are about the same. However, of the samples grown at the low temperature, the photon emission efficiency of ZnO on GaN is much higher than that of ZnO on sapphire.

EE10.20
Effects of Growth Temperature on Nano-structure Characteristics of ZnO Thin Films on Sapphire.
Shu-Cheng Chin[1], Chun-Yung Chi[1], Wen-Yu Shiao[1], Fang-Yi Jen[1], Yen-Cheng Lu[1], Lin Hong[1], Yu-Li Lin[1], Chih-Chung Yang[1], Bao-ping Zhang[2] and Yusaburo Segawa[2]; [1]Institute of Electro-Optical Eng., National Taiwan University, Taipei, Taiwan; [2]Photodynamics Research Center, the Institute of Physical and Chemical Research, Sendai, Japan.

The nanostructures of ZnO heavily rely on the growth conditions, particularly on the growth temperature and pressure. By decreasing the growth pressure, the ZnO nanostructures change from nano-rods into nano-tubes and then nano-walls. ZnO nano-rods, nano-tubes, and nano-walls are normally obtained at 10-6, 1-0.3, and 0.1-0.06 Torr, respectively, in growth pressure. In growth temperature dependence, when the growth temperature is lower than 250^{circ}C, smooth surfaces without grain formations were observed. The diffusion of atoms on the surface is suppressed at low growth temperatures. However, when the growth temperature is high, the kinetic energy of zinc atoms becomes high, and it is expected that the zinc atoms will become more diffusive on the substrate surface and select sites having smaller lattice mismatch. When the growth temperature is higher than 300^{circ}C, we can normally observe that the unit cell of ZnO is twisted in the c-plain by 30o with respect to that of Al2O3. The in-plane orientation can be controlled by an appropriate selection of the growth temperature that can lead to different growth modes at the initial stage of growth. In this research, we compare the nano-structures of three samples of ZnO thin film on sapphire under different growth temperature conditions. Although disconnected spiral domain structures (on the scale of 100 nm in size) are observed in the samples of high-temperature (450^{circ}C) growth, their crystal quality is generally better than the one grown at a low temperature (200 oC), either near or away from the sapphire interface. Lattice misfits and threading dislocations are observed within a domain with the separation of around 8 nm. The sample grown at the low temperature shows a connected structure through the ZnO layer. However, its crystal quality is relatively poorer. Of the two samples with high-temperature growth, the one with initial low-temperature growth has a larger domain structure (around 150 nm in size) and relatively lower crystal quality. In particular, strong strains exist near the interface of this sample. The samples of high-temperature growth generally have higher photon emission efficiencies.

EE10.21
Manipulation of ZnO Nanowire by Low-Temperature Solution Approach. Chia-Hsin Lin, Materials Research Laboratories, Industrial Technology Research Institute, Chutung, Hsinchu, Taiwan.

A catalyst free, structure-induced heterogeneous nucleation and direct growth of ZnO nanowires on organic and inorganic substrates was prepared by low-temperature solution approach process. The experimental results showed that ZnO nanowires could be directly synthesized upon the concave of substrate without any pre-seeding. In this work ZnO nanowires were grown on both polystyrene bead layer and physical-grinded wafer substrate. ZnO nanowires with a broad aspect ratio of 0.01 $\sim$ 100 was controlled mainly by adjusting of reactant concentration and pH state of solution. A needle-like ZnO nanotip were also prepared by a two-step limited growth condition as a result of several nanometers only, which is highly in favor of the field emission. ZnO nanotips showed a turn-on voltage as low as 3V/μm and a high emission current density of 2mA/cm2 under the field of 7.5V/μm. These unique characteristics were attributed to a high aspect ratio of ZnO nanowire and a direct growth upon the surface of substrate without the influence of barriers such as catalyst layer. Structure-induced heterogeneous nucleation and growth facilitates the fabrication of ZnO nanowires as a result of low turn-on voltage and high emission current density, that makes ZnO nanowires as the potential photoeletronic units in field-emission displays.

EE10.22
Electrical Properties of Diamond MISFETs with Submicron Gate on Boron-doped (111) Surface. Kyung-ho Park[1], Takeyasu Saito[1], Kazuyuki Hirama[2], Hitoshi Umezawa[1], Mitsuya Satoh[2], Hiroshi Kawarada[2] and Hideyo Okushi[1]; [1]Diamond Research Center, AIST, Tsukuba, Japan; [2]Department of Electrical Engineering and Bioscience, Waseda University, Tokyo, Japan.

Diamond semiconductor devices are expected to be of importance for high power and high frequency applications based on its excellent properties. Fabrication of low resistive semiconductive diamond is still difficult, naturally, diamond devices technology is limited to the one of H-terminated surface conductive layer with high surface carrier density. Moreover, majority of such activities have been carried out on the (100) oriented surface due to two reasons, availability of substrate and its smooth surface morphology. Based on the devoted works as to MESFET and MISFET on H-terminated surface on (100) substrate, the cut-off frequency over 20 GHz was achieved recently. On the other hand, limited number of devices characteristics on H-terminated (111) surface were reported. Moreover, besides several diamond process Integration issues, such as, contact formation, and gate fabrication, there are still very limited number of information available for the best matiching materilas of the gate insulator, and passivations. In this study, the p-type surface conductive layer of B-doped diamond on (111) was employed to fabricate MISFETs using three kinds of gate insulators, namely CaF2, SiO2 and Al2O3 with submicron gate length. We present comparative study between properties of (100) surface and (111) surface with each device features. As well, what is appropriate Gate insulator materials for the diamond device under normal requirements, such as low leakage and low surface states, high breakdown voltage, and no damage for H-terminated surface. The CVD Diamond homoepitaxial (111) layer showed the sheet resistivity, surface mobility and carrier concentration of H-terminated surface condition in the air were 10kOhm/sq, 35cm2/Vs, 2E+13/cm2, respectively, when bulk carrier concentration is 3E+15/cm3. The carrier mobility on hydrogenated (111) surface acquired in this study was found to show clear dependency on CH4/H2 concentration from 0.1% to 1.5% in the air. This value was still a quarter of that obtained on (100) samples. In MISFET fabrication processes, Au evaporation on H-terminated region was employed as the source and the drain. Inductively coupled plasma etching process was used for the isolation procedures. Self-aligned gate formation processes with 1 -4um gate lengths were carried out by employing (CaF 2, SiO2 , Al2O3) and Cu stacked GOI structures. Sample of CaF2 gate (111) MISFET exhibited comparable characteristics, Id, gm and RF performance with (100), suggesting that there is no major differences in different H-terminated surface utilized devices. The maximum drain current and transconductance as 240mA/mm and 85mS/mm, respectively, were obtained. This exhibited the cut-off frequency as 4GHz, which is one of the best value among (111) derived diamond FET to date. This work was carried out under Advanced Diamond Devices Project, The New Energy and Industrial Technology Development Organization (NEDO), Japan.

EE10.23
Barium Trace Detection in Oriented ZnO Films Grown by MOCVD. Laxmikant Saraf[1], Zheming Wang[2], Scott Lea[1], Mark Engelhard[1], Chongmin Wang[1], David McCready[1] and Scott Chambers[2]; [1]Environmental Molecular Sciences Laboratory, Pacific Northwest National Laboratory, Richland, Washington; [2]Fundamental Science Division, Pacific Northwest National Laboratory, Richland, Washington.

Excellent optical emission properties of ZnO can potentially be used to detect the effect of dopants in it, which potentially can be used for the trace detection related applications. The structural anisotropy in hexagonal ZnO makes it easier to naturally grow oriented ZnO films in c-axis out-of-plane direction. We are in a process to study barium contamination effects in oriented ZnO films grown by MOCVD. In this study, ZnO thin films were grown on Si(100) by MOCVD at 10 Torr combined partial pressure of oxygen and argon with a total gas flow of $\sim$2500 sccm. Initial emission tests at liquid helium temperatures indicate an extra emission peak at 355 nm apart from normally observed ZnO emission band in the range of 360 nm to 400 nm. Detailed analysis on these samples is also carried out by using XRD, AES, XPS and HRTEM to establish a correlation between structural and surface properties with its emission properties. HRTEM measurements indicate excellent alignment of ZnO atomic

planes parallel to Si (100) surface. These results are discussed in the context of selective substitution of future magnetic element dopants and/or trace contaminants in ZnO to modify its physical properties in order to tune them for exciting applications in the area of spintronics and sensors.

EE10.24
On the role of group I elements in ZnO. Bruno Meyer[1], Joachim Sann[1], Niklas Volbers[1], Arndt Zeuner[1], Axel Hoffmann[2] and Ute Haboeck[2]; [1]1. Physikalisches Institut, Giessen, Germany; [2]Solid State Physics Institute, Berlin, Germany.

Diffusion of Li, Na and K into single-crystal substrates of ZnO were performed. We compare the results with ZnO epitaxial films doped with the respective elements during growth. The diffused and in-situ doped layers were studied using mass spectroscopy, low temperature photoluminescence and Raman spectroscopy. Li and Na are known to produce deep acceptor centers which give rise to shallow donor to deep acceptor recombinations in the visible spectral region. We will demonstrate that also shallow acceptors are introduced having binding energies around 300 meV. A donor-acceptor pair recombination (zero phonon line at 3.05 eV) with LO phonon replica is observed analogous to the "edge" emission in other II-VI compounds.

EE10.25
A TEM Investigation of the Nitrogen Effect on The Structure of Mn-Doped Zno Thin Films Deposited by RF Magnetron Sputtering. Ruterana Pierre[1], Morad Abouzaid[1], C. Liu[2] and Hadis Morkoc[2]; [1]SIFCOM, ENSICAEN, caen, France; [2]VCU, Richmond, Virginia.

For Mn-doped ZnO thin films, deposited by using RF magnetron sputtering on c-plane sapphire substrates, the magnetic properties of the Mn-doped ZnO films have been measured by a superconducting quantum interference device magnetometer. Magnetization vs. magnetic field hysteresis was observed at room temperature. Codoping with nitrogen increases the magnetization of the layers. Using transmission electron microscopy we investigate the evolution of the crystalline quality with the nitrogen codoping. The results show that the magnetic properties are enhanced in the best crystalline quality layers which do not exhibit phase separation in form of precipitates. Their columnar structure due to rf sputtering is not disturbed in these Mn and N doped layers. The origin of the ferromagnetic properties of the Mn-doped ZnO film will be discussed.

EE10.26
Acceptor doping of ZnO layers: Comparison of mono- and co-doping approaches. Andre Krtschil, Armin Dadgar, Nikolay Oleynik, Annett Diez and Alois Krost; Institute of Experimental Physics, Otto-von-Guericke-University of Magdeburg, Magdeburg, Germany.

Despite a lot of research activities, successful acceptor doping in terms of stable p-type conductivity remains one of the major bottlenecks for ZnO-based optoelectronics. In order to better understand this topic, in this contribution we compare several doping approaches: conventional mono-doping with two potential acceptors, i.e. arsenic and nitrogen, as well as co-doping with both species. The special focus of our investigations concerns the doping impact on the local electrical properties and their appearance in integral characteristics. The samples under study were grown by metalorganic vapor phase epitaxy in a two-step growth process on GaN on sapphire templates. After the growth of a ~300 nm thick ZnO layer deposited at 450°C using DMZn and tert-butanol a high temperature ZnO layer was grown at 850°-900°C using DMZn and N2O. For doping experiments, the high temperature layer was doped with arsenic using AsH3 and nitrogen using unsymmetrical-dimethylhydrazine. The local conductivity type was determined by scanning capacitance microscopy (SCM), a method based on an atomic force microscopy setup which measures the local carrier concentration via the local C-V-curves with a spatial resolution in the order of some tens of nanometers. We find in SCM that all mono-doped layers exhibit large n-type regions, but very local p-type or depleted inclusions around grain boundaries and growth defects. Conventional macroscopic C-V-analysis by a mercury probe reveals exclusively n-type depletion in these cases. Interestingly, for all co-doped layers this situation is completely inverted. Now, we mostly observe a so-called mixed conductivity instead of uniform carrier concentration and conductivity type, i.e. largely extended p-type domains for smooth two-dimensional parts of the layer as well as local n-type regions at three-dimensional islands and defects. Macroscopic C-V-curves exhibit depletion in both voltage bias directions due to the coexisting n- and p-type regions. Furthermore, the doping parameters were slightly varied to optimize the structural quality of the doped layers and to reduce the growth defects. As best result, we achieved a nearly homogeneous p-type layer ($50x50\mu m^2$ scan area during SCM) containing only very few defects with corresponding carrier concentrations in the 10^{15} cm^{-3} range as determined from integral C-V-curves. The observed p-type conductivity after co-doping with As and N is reproducible for the whole sample set and long-time stable since several months.

EE10.27
Hydrothermal growth of transition metal doped ZnO single crystal. Young Kuk Lee, Korea Research Institute of Chemical Technology, Taejon, South Korea.

Transition metal (Mn and Fe) doped ZnO single crystals were grown by hydrothermal method using a Pt- and Ag-lined high pressure autoclave in KOH-based hydrothermal solution. Dimension of the as-grown single crystal is up to 40 X 30 X 10 mm^3, which can be fabricated to 1-inch ZnO crystal substrate. Maximum growth rate were about 0.23mm/day. X-ray photoemission study showed that the Mn ion located at Zn site substitutionally. Some important structural optical and magnetical properties of transition metal doped ZnO single crystals are also discussed.

EE10.28
Nitrogen Incorporation Kinetics in Organometallic Vapor Phase Epitaxy of (In)GaAsN/GaAs(001) Using 1,1-Dimethylhydrazine. Jean-Nicolas Beaudry[1,2], Remo A. Masut[1,2,3] and Patrick Desjardins[1,2]; [1]Engineering Physics Department, Ecole Polytechnique de Montreal, Montreal, Quebec, Canada; [2]Regroupement quebecois sur les materiaux de pointe, Montreal, Quebec, Canada; [3]Instituto de Ciencia de Materiales de Madrid, Madrid, Spain.

The current strong interest in dilute semiconductor nitrides stems from the fact that the addition of N in semiconductors such as GaAs reduces both the band gap and the lattice constant. These alloys also present very advantageous band alignment characteristics. These properties make them prime candidates for the fabrication of, for example, semiconductor lasers operating at telecommunication wavelengths. The key challenges to their integration in devices arise from the fact that N atoms are very small compared to the host. This leads to the so far uncontrolled incorporation of N on non-substitutional lattice sites and to a degradation of the optical properties with increasing N content. Our high-resolution x-ray diffraction results combined with secondary ion mass spectrometry analyses indicate that non substitutional N incorporation begins at x=0.03 in GaAsN as the perpendicular lattice parameter decreases faster than that predicted by Vegard's rule. A prerequisite for the accurate control of N incorporation in $(In_y)Ga_{1-y}As_{1-x}N_x$ alloys during organometallic (OM) vapor phase epitaxy is a detailed understanding of the growth kinetics and surface processes. We have thus carried out a comprehensive study of the effect of growth temperature (T_s), growth rate, V/III ratio and reactor pressure on the incorporation of N. The samples were grown from trimethylindium, trimethylgallium, tertiarybutylarsine (TBAs), and 1,1-dimethylhydrazine (DMHy). Our complete set of results reveal two distinct growth regimes above and below 550°C.The N incorporation ratio $[N] = x(1-X_v)/X_v(1-x)$, where $X_v = J_{DMHy}/(J_{TBAs} + J_{DMHy})$ is the OM flux ratio in the vapor phase, is affected by T_s and J_{DMHy} in an entangled way due to the complex pyrolysis of DMHy. [N] is rather low (0.0033) at 550°C and decreases even more with increasing temperature, being essentially zero at 650°C. [N] increases slightly to 0.0039 with T_s decreasing to 500°C, likely due to the incomplete pyrolysis of DMHy, known to involve byproducts such as the unstable NH_2, in cold-wall reactor. We attribute the reduction in [N] at higher T_s to the parasitic decomposition of DMHy and the desorption of N-rich species as NH_2 tends to transform to more stable NH_3. At 575°C and above an increase in DMHy partial pressure (X_v from 0.44 to 0.92) results in higher growth rates. This is concomitant with the change in nitrogen incorporation from one regime to the other as Ga incorporation is promoted by a reaction involving the TMGa-DMHy adduct in the high temperature regime. For extremely large DMHy flow rates ($X_v > 0.94$ at 575°C), growth becomes nearly completely inhibited due to the passivation of the surface by DMHy. In these conditions, N incorporation in the solid phase increases sharply ($x > 0.15$) as the surface morphology of these extremely thin films is strongly degraded. Practically, N incorporation in $GaAs_{1-x}N_x$/GaAs(001) is therefore limited to about x = 0.038.

EE10.29
Composition Modulation and Local Structure in Strained Diluted GaInNAs Nitride Alloy Thin Layers. Arnaud Metsue and Catherine Priester; ISEN, Epiphy, IEMN, Villeneuve D'ascq Cedex, France.

Ga—GaInNAs quantum wells on GaAs substrates appear to be very attractive for promising applications (lasers for telecommunication, solar cells) but the question of composition modulation may strongly alter the optical or elelectronic properties of the heterostructures [1,2]. Thanks to the large difference of lattice parameters of the binaries involved in this quaterneray alloy, the local structure of such alloys

can be experimentally investigated by making use of EXAFS, for example [3,4]. In the theoretical work reported here, we focus on correlation between local chemical atomic neighborhood and atomic distances. The model used is Valence Force Field approximation, and we modelize a periodic $Ga_{1-x}In_x N_yAs_{1-y}$ alloy (period up to 32 atomic row) film (typically 24 atomic planes thick) deposited on GaAs substrate. We have chosen to report results for y=.01,.02,.03 and .04 and x=.0625,.120,.25 and .375. The surface is dimerised (for simplicity we consider 2x1 anion rich surfaces). We start from random films and calculate first and second nearest neighbor distances and draw the corresponding spectra, then we allow the N atoms to choose their optimal location. This pseudo-annealing strongly enhances the number of In-N bonds, in agreement to experimental studies [3]. For each distance one can check the local chemical arrangement, and, from this statistical study, show that fine structure of each peak of the spectra cannot be directly related to a given chemical distribution up to 3rd nearest neighbors. The position of the peaks appear not to be modified by alloy composition nor alloy segregation, which only alter relative intensities and peak shapes. Last, guided by experimental observation [2], we consider stripes of In-rich and In-poor zones : calculated energy variations show a strong tendency for N atoms to completely desert In-poor zones. References [1] K. Kim, A.Zunger, Phys. Rev. Lett.86,2609 (2001) [2] J.-M Chauveau et al,Journal of crystal growth, vol. 251, p. 383-387 (2003) [3] K. Uno et al, Japanese Journal of Applied Physics, vol. 43, p. 1944-1946 (2004) [4] G.Ciatto et al. Phys .Rev. B 71, 115210 (2005)

EE10.30
Abstract Withdrawn

EE10.31
Comparison of Lasing Characteristics of GaInNAs Quantum Dot Lasers and GaInNAs Quantum Well Lasers. Chongyang Liu, Soon Fatt Yoon and Zhongzhe Sun; School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore, Singapore.

Recently, there has been considerable interest in GaInNAs material grown on GaAs substrate, for realizing low-cost, high-performance and high-temperature laser diodes in the 1.3-μm wavelength regime. Both GaInNAs quantum dot (QD) lasers and GaInNAs quantum well (QW) lasers have been realized. This paper reports the comparison of lasing characteristics of GaInNAs QD lasers and GaInNAs QW lasers. GaInNAs/GaAsN self-assembled QD lasers, grown using solid source molecular beam epitaxy (SSMBE), have been fabricated. The GaInNAs QD laser worked under continuous wave (CW) operation at room temperature (RT), with the emission wavelength centered at 1175.86 nm. The GaInNAs QD laser, with the dimension of 50 x 2000 μm^2, has a CW, RT threshold current of $\sim$ 2.1 A, corresponding to a threshold current density of $\sim$ 2.12 kA/cm^2. Light output power of 16 mW/facet was achieved from this device, which corresponds to an external quantum efficiency of 14.6%. From the temperature-dependent light output power versus injection current (P-I) characteristics of a GaInNAs QD lasers with the dimension of 50 x 1060μm^2 under pulsed measurements, characteristic temperature (T_0) was estimated to be around to 79.4 K in the temperature range of 10 $\sim$ 60 ^{o}C. Temperature-dependent P-I characteristics (10 $\sim$ 50 ^{o}C) were also measured from GaInNAs QD laser with longer cavity length (L) of 1700 μm. The laser could only work up to 45 ^{o} C, and yielded T_0 of 65.1 K. T_0 decreased with increasing cavity length instead of increasing, which is normally observed for the semiconductor lasers. We attributed the observed abnormal phenomena to the nonuniformity of the GaInNAs QD laser structure. GaInNAs single-quantum-well (SQW) and triple-quantum-well (TQW) lasers, grown with metal organic chemical vapor deposition (MOCVD), were also fabricated and characterized. Extremely low threshold current of 15.7 mA was obtained from GaInNAs SQW lasers (4 x 500 μm^2), with the emission wavelength at 1247 nm, under RT, CW operation. Temperature-dependent P-I characteristics (20$\sim$80 ^{o}C) were measured from GaInNAs SQW laser with L of 500 and 1500 μm, respectively. T_0 was estimated to be 62.4 K for the GaInNAs SQW laser with L=500 μm. In contrast to that of GaInNAs QD lasers, T_0 for the GaInNAs SQW laser with longer cavity length, L=1500 μm, is a little higher, which is 78 K. GaInNAs SQW laser showed strong temperature dependence of threshold current and presented much lower T_0 than that of GaInNAs TQW lasers, which RT, CW emission wavelength is centered at 1297 nm. For comparison, T_0 of GaInNAs TQW lasers (L=500 μm) is 143.5 K, and 157.2 K for L=1500 μm. Our work implies that with the multiple quantum well (MQW) structure, T_0 value of GaInNAs QW lasers could be greatly improved.

EE10.32
Optimization Of Growth Temperature of Ga(In)NAs Thin Films Grown by Atomic Hydrogen Assisted Rf-Mbe. Yukiko Shimizu, Naoya Miyashita, Akira Uedono and Yoshitaka Okada; Inst. of Applied Physics, Univ. of Tsukuba, tsukuba, Ibaraki, Japan.

GaInNAs alloys have found wide practical applications ranging from long-wavelength optical communication semiconductor lasers to high-efficiency multi-junction solar cells. The major advantage of this alloy is that the addition of a few atomic percent of N in GaAs causes a gigantic reduction in band gap energy, and that it can be lattice matched to GaAs substrate by controlling the [N]/[In] composition ratio to $\sim$ 3. However, both the optical and electrical properties of GaInNAs films, in general, become increasingly degraded with increasing N composition. The mechanism for the degradation is not fully understood, although low miscibility of N in GaAs strongly affects the growth mechanism and is known to result in segregation and clustering. Recently, we have shown that irradiation of low-flux atomic hydrogen during RF-molecular beam epitaxy (H-MBE) results in an improved material quality as hydrogen acts as a suitable surfactant promoting an ideal layer-by-layer growth mode. As a continuing effort, we have investigated the effect of growth temperature on the crystal quality of Ga(In)NAs grown by atomic H-assisted RF-MBE. Throughout the growth, atomic H was irradiated to the substrate as before. The growth temperature was varied over a wide range of 340 $\sim$ 520 $^\circ$C, and the growth was monitored in-situ using reflection high-energy electron diffraction. We find that Ga(In)NAs films fabricated at lower growth temperatures generally result in improved crystal quality and narrower peak linewidths ($\sim$ 64 arcsec for 340°C) as determined from high resolution X-ray diffraction and photoluminescence. Further, since N-related deep-level defects, which are responsible for determining the final device performance is related to the vacancy-type defects, we performed positron annihilation measurements. We find, for the first time, that the vacancy-type defect densities in Ga(In)NAs films are related to both atomic H flux during MBE growth as well as growth temperature.

EE10.33
Potentially Modulated GaAs/GaNAs/InGaAs Quantum Wells for Solar Cell Applications. Naoto Kobayashi, Naoyuki Sasaki and Yoshitaka Okada; Institute of Applied Physics, University of Tsukuba, Tsukuba, Ibaraki, Japan.

Recently, multi-quantum well (MQW) solar cells have attracted an increasing interest for achieving higher efficiency photovoltaic and solar energy conversion. The fundamental principle is such that a MQW, which is introduced in the intrinsic region of p-n or p-i-n solar cell of wider bandgap (barrier) material, can be used to increase the photoabsorption in the energy region below the absorption edge of host material. However, the superior performance of MQW solar cells can only be expected if the escape rate of photogenerated carriers out of QWs is kept sufficiently high and minimizing the radiative losses within QWs. Previously, we have shown that compared to a conventional square-shaped GaAs/InGaAs MQW solar cell, the carriers escape out of QWs more efficiently in multi-step potentially modulated structures resulting in a better photovoltaic performance. However, due to the large lattice-mismatch with GaAs, In content in InGaAs QW cannot be increased to more than $\sim$ 20%, or otherwise, dislocations would be generated and recombination current would increase dramatically. In this work, the photovoltaic performance of GaAs/GaNAs/InGaAs MQW solar cells were investigated. The purpose of introducing GaNAs material is of two-fold; One is that GaNAs would induce a tensile strain that compensates the compressive strain induced by InGaAs, which thus adds a degree of freedom in optimizing the MQW structure. The other is GaNAs/InGaAs interface could become a type-II interface by adjusting the N to In composition, which would facilitate spatial separation of electrons and hole wavefunctions leading to suppressed recombination losses. For this purpose, we have fabricated various 10-period GaAs(50nm)/GaNAs/InGaAs MQWs introduced into the intrinsic region of GaAs p-i-n solar cells by atomic H-assisted RF-molecular beam epitaxy. We show, for the first time, that GaAs/GaNAs/InGaAs MQW solar cells exhibit improved external quantum efficiencies in the low energy region (880$\sim$1000nm) compared to the conventional GaAs(50nm)/InGaAs(10nm) MQW cells.

EE10.34
Evidence of two different mechanisms at the origin of the blue shift after annealing of GaInNAs QWs. Maxime Hugues, Benjamin Damilano, Jean-Michel Chauveau, Jean-Yves Duboz and Jean Massies; Centre de Recherche sur l'Hetero-Epitaxie et ses Applications, Centre National de la Recherche Scientifique, 06560 Sophia Antipolis, France.

The incorporation of small amount of nitrogen in InGaAs/GaAs results in a band-gap reduction which opens the way to the realization of telecom lasers on GaAs substrates. However, the radiative efficiency of GaInNAs (GINA) quantum wells (QW) is strongly degraded due to the incorporation of nitrogen. Post-growth annealing are required to improve the photoluminescence (PL) properties but unfortunately the emission shifts towards shorter wavelengths. This PL blue shift (BS) is generally attributed to two different mechanisms: In-Ga or As-N

interdiffusion, and atomic reorganization of the N-neighborhood. It has been reported that interdiffusion processes in InGaAs QWs induce PL emission BS of hundreds of meV depending on the annealing temperature (AT). However, in the case of GINA QWs, it is generally found that the annealing does not induce interdiffusion. Also, it has been shown theoretically and experimentally that local environment changes of N atoms lead to a strong band-gap BS. Actually, there is still an ambiguity on the origin of the PL BS of GINA QWs upon annealing. The objective of this study is to discriminate the role of these two suggested mechanisms on the spectral BS of annealed GINA QWs. For this purpose, rapid thermal annealings of GINA QWs with high In and N contents were carried out under N2 flow for 30 sec at temperatures ranging from 575 to 900°C. The PL BS shows the same trend for all the studied samples. For annealing temperature (AT) below 700°C, the BS increases almost linearly while it saturates at 100 meV for AT between 700°C and 800°C. However, above 800°C, the BS rapidly increases. Both as-grown and 700°C annealed samples were investigated using transmission electron microscopy (TEM). The QW width is unchanged and the image contrast is identical indicating no compositional change. These observations lead to the conclusion that the BS mainly comes from atomic reorganization for this range of AT. On the other hand, after annealing at temperature higher than 800°C, the (004) x-ray rocking curve reveals that the QW becomes wider. This indicates an important interdiffusion process. This is confirmed by TEM analysis : the QW thickness increases while the composition is strongly modified. The BS for ATs > 800°C is therefore due to a diffusion process. Two samples based on InGaAs and GaAsN ternary QWs have been studied to determine if the BS in GINA QWs is dominated by In-Ga or N-As interdiffusion. In the case of GaAsN, the BS is very low even for annealing up to 900°C while in the case of InGaAs QW, the BS increases rapidly above 700°C. This means that the BS observed after annealing at high temperature is dominated by In-Ga interdiffusion for GINA QWs. To conclude, the blue shift of GINA QWs comes from two mechanisms : atomic reorganization for annealing temperature below 800°C and In-Ga interdiffusion for annealing temperature above 800°C.

EE10.35
Characterization of a Dominant Electron Trap in GaNAs Using Deep-Level Transient Spectroscopy. Steven Johnston and Sarah Kurtz; National Renewable Energy Laboratory, Golden, Colorado.

Both p-type and n-type dilute-nitrogen GaNAs epitaxial layers grown by metal-organic chemical-vapor deposition were characterized by deep-level transient spectroscopy (DLTS). For each case, the dominant DLTS signal corresponds to an electron trap having an activation energy of about 0.25 eV for p-type GaNAs and about 0.35 eV for n-type GaNAs. In p-type GaNAs, the electron traps fill slowly, as the DLTS signal reaches saturation using zero-bias filling pulses with widths on the order of 1 to 10 seconds. The long filling times correspond to the potential barrier that electrons must surmount at low temperature in order to fill traps in the p-type region by traveling from the n-type region. When applying a wide range of filling-pulse widths, the activation energy tends to decrease from about 0.3 eV for short filling-pulses to about 0.2 eV for longer filling-pulses. The trap density is proportional to nitrogen content for these dilute-nitrogen samples. In n-type GaNAs, the electron-trap density is also proportional to nitrogen content. For constant nitrogen content, the electron-trap density increases with increasing n-type doping. The electron traps fill quickly in the n-type GaNAs, as the DLTS signal approaches saturation in microseconds. The capture cross-sections determined by the DLTS Arrhenius plots are typically about 10^{-13} to 10^{-12} cm^2. The electron-trap densities range from 10^{15} to 10^{16} cm^{-3} in mid-10^{17} cm^{-3} n-type-doped GaNAs having a bandgap of 1.35 to 1.4 eV. These trap parameters give an estimated carrier lifetime of 1 ns or substantially shorter.

EE10.36
Growth and Properties of Lattice Matched GaAsSbN Epilayer on GaAs for Solar Cell Applications.
Sudhakar K. Bharatan[1], Shanthi Iyer[1], Kalyan Nunna[1], Ward J. Collis[1], Jia Li[1], Liangjin Wu[1] and Kristopher McGuire[2]; [1]Electrical Engineering, North Carolina A&T State University, Greensboro, North Carolina; [2]Physics and Astronomy, University of North Carolina, Chapel Hill, North Carolina.

In this work, the growth and characterization of 1.0 μm thick GaAsSbN bulk layers nearly lattice matched to GaAs, grown in an elemental solid source molecular beam epitaxy (MBE) system with a RF plasma nitrogen source, is discussed. The substrate temperature in the range of 450-470°C is found to be optimal. These layers exhibit significant improvement in photoluminescence (PL) properties following annealing, either in ex situ in N ambient or in-situ under As overpressure. Effects of in situ and ex situ annealing for different time on the PL peak position and PL intensity are also discussed. The PL temperature dependence studies are also carried out on these samples which indicates evidence of "inverted s-shaped" behavior in the low temperature regime. The composition of the grown structure is investigated by high resolution x-ray diffraction (HRXRD) and secondary ion mass spectroscopy (SIMS) analysis. The N and Sb compositions in these layers have been estimated to be around $3\frac{0}{00}$ and $7\frac{0}{00}$, respectively, from HRXRD and SIMS measurements. The 10K PL peak energy of 1eV with a FWHM of 18meV has been achieved on ex-situ annealed samples in N ambient. The layers are found to be fully strained as evidenced by the presence of high frequency fringes on the x-ray diffraction spectra. Raman spectroscopy analysis has also been carried out on both as grown and annealed samples to determine the local bonding of various elements.

EE10.37
White-light Emitting ZnO-SiO2 Nanocomposite Thin Films Prepared by Sputtering Method. Yun-Yung Peng[1], Tsung-Eong Hsieh[1] and Chia-Hung Hsu[2]; [1]Materials Science and Engineering, National Chiao Tung University, Hsinchu, Taiwan; [2]Research Division, National Synchrotron Radiation Research Center, Hsinchu, Taiwan.

ZnO-SiO2 nanocomposite thin films were prepared using RF sputtering method without substrate heating. The PL measurements show that the ZnO nanoparticles embedded in the SiO2 matrix emit white-light consisting of violet, blue, and green-yellow band emissions. The presence of the blue emission was attributed to the large amount of ZnO/SiO2 interfaces, which enlarges the depletion layer width and then enhances the related transition. The results of the Gaussian curve fitting revealed the competition between the blue and green-yellow band emissions and the relative emission intensity is strongly associated with the amount of the ZnO nanoparticles embedded in the SiO2 matrix. Further analyses indicated that the defect structure of samples could be manipulated by the amount and distribution of ZnO nanoparticles in SiO2 matrix to yield distinct luminescence spectrum.

SESSION EE11: Dilute Nitride and Bismide Semiconductors
Chairs: Satyen Deb and Angelo Mascarenhas
Thursday Morning, December 1, 2005
Constitution B (Sheraton)

8:00 AM *EE11.1
Single Impurity Spectroscopy in a Semiconductor.
Sebastien Francoeur[1], J. F. Klem[2] and A. Mascarenhas[1]; [1]National Renewable Energy Laboratory, Golden, Colorado; [2]Sandia National Laboratories, Albuquerque, New Mexico.

The ability to probe single, isolated and spatially resolved entities permits the observation of their intrinsic, singular, and hidden properties otherwise masked by ensemble averaging. This has led to remarkable progress in the understanding of single atoms, molecules, defects, quantum dots, and carbon nanostructures. Until now, little progress has been done in the study of a single impurity in a semiconductor material. We report on the fine structure luminescence from a single impurity center in a semiconductor. The host is GaAs and the impurity corresponds to two nitrogen atoms forming a pair. The selective study of a single impurity pair unveils its unique characteristics and allows the analysis of 1) its symmetry and its effects on the fine structure of the luminescence, 2) the spatial and orientationnal distribution of pairs, 3) the effects of the environment on its characteristics, and 4) the renormalization of its energy due to many-body effects. We find that circumventing the limitations imposed by ensemble averaging provides an unprecedented perspective on the nanoscience of impurities. These findings help reconsider the traditional role of impurities and open up many possibilities for technological applications.

8:30 AM EE11.2
Nitrogen Incorporation and Magneto-optical Studies of GaAsSbN/GaAs Single Quantum Well Structures.
Kalyan Nunna[1], Shanthi Iyer[1], Liangjin Wu[1], Sudhakar Bharatan[1], Jia Li[1], Ward J Collis[1], Krishan Bajaj[2], Tugrul Senger[3] and Xing Wei[4]; [1]Electrical and Computer Engineering, North Carolina A&T State University, Greensboro, North Carolina; [2]Physics, Emory University, Atlanta, Georgia; [3]Physics, Bilikent University, Ankara, Turkey; [4]NHMFL, Florida State University, Tallahassee, Florida.

A systematic study has been carried out on GaAsSbN/GaAs Single Quantum Well (SQW) structures with different N concentrations grown at 470°C in an elemental solid source EPI 930 molecular beam epitaxy (MBE) system using a RF plasma assisted nitrogen source operating at 300W. The nitride QW samples were in-situ annealed in As ambient at 650°C for 10 minutes. The compositions of these alloys were determined using a combination of secondary ion mass spectroscopy and high-resolution x-ray diffraction measurements. Low

10K PL peak energy of 0.78 eV with low FWHM of 28meV was achieved on SQWs for N concentration of 1.4$\frac{0}{00}$. The optimum range of N flux based on low PL energy and FWHM is found to be 2-7x10^{-7} torr. Magneto-photoluminescence properties of these coherently strained SQW structures of various N concentrations were also investigated in this work. The variations of the diamagnetic shifts in the GaAsSbN/GaAs SQWs as a function of magnetic field were measured up to 32 T at 1.3K.The diamagnetic shifts observed were in the range of 11-15 meV, for a change in the magnetic field by 32T. These values are considerably larger than those reported in similar QW structures by Senger et al.[1]. Calculations have been performed using models based on both free and localized excitons using variational approaches for quantitative explanation of our data. Our preliminary analysis seems to indicate that GaAsSbN/GaAs system is a type I structure as expected. These studies allow us to determine the values of the effective masses of electrons and holes in these structures. The details of these investigations along with our observed differences in the values of the diamagnetic shifts from those reported in literature will be presented. Supported by Army Research Office (Grant No. W911NF-04-1-0025), and NASA (Grant No. NAG3-2782). Reference [1] Senger, R.T., et al., Appl. Phys. Lett. 83, 5425-5427 (2003).

8:45 AM EE11.3
Electronic Properties of (In)GaAsN/GaAs(001) Heterostructures: Analysis of the E_+ Transition and the Effect of In Incorporation. Stephane Turcotte[1,3], Nikolay Shtinkov[1,3], Jean-Nicolas Beaudry[1,3], Ghaouti Bentoumi[2,3], Remo A. Masut[1,3,4], Richard Leonelli[2,3] and Patrick Desjardins[1,3]; [1]Engineering physics, Ecole Polytechnique de Montreal, Montreal, Quebec, Canada; [2]Physics Department, Universite de Montreal, Montreal, Quebec, Canada; [3]Regroupement Quebecois sur les Materiaux de Pointe, Montreal, Quebec, Canada; [4]Instituto de Ciencia de Materiales de Madrid, Madrid, Spain.

Dilute semiconductor nitride heterostructures present unusual electronic properties related to the well known splitting of their lowest conduction band into E_+ and E_- sub-bands whose exact origin is still a subject of debate. In particular, $In_yGa_{1-y}As_{1-x}N_x$ is an appealing candidate for applications such as photovoltaic cells and telecommunication lasers as it can be grown lattice-matched to GaAs. Using a combination of optical spectroscopy techniques and tight-binding[1,2] electronic structure calculations, we have studied a series of single layer $GaAs_{1-x}N_x$ alloys on GaAs(001) as well as $In_yGa_{1-y}As_{1-x}N_x$ single layers nearly lattice-matched (mismatch below 0.1%) to GaAs(001) substrates (y $\sim$ 3x) grown by organometallic vapor phase epitaxy. Variable angle spectroscopic ellipsometry spectra from these alloys are characterized by an extra feature compared to typical GaAs data that can be clearly assigned as the E_+ transition contribution. Using the layer thickness precisely determined by high resolution X-ray diffraction measurements, we obtain the absolute absorption coefficient (α) near threshold from absorption spectroscopy. We find that the values of α near the absorption edge for the GaAsN layers are slightly lower than those for the corresponding InGaAsN layers at a given nitrogen fraction. Since α values for the dilute nitrides are close to the known value of α for GaAs ($\sim 10^4$ cm^{-1}), we conclude that the E_+ transition cannot be adequately explained by considering only two interacting conduction bands close to the Γ point. Rather, contributions from the whole Brillouin zone must be included to explain this transition. The results also suggest that incorporation of indium affects only slightly the band structure of the dilute nitride. The difference in the experimental values for absorption edges between $GaAs_{1-x}N_x$ and $In_{3x}Ga_{1-3x}As_{1-x}N_x$ layers with the same nitrogen content increases up to 80 meV (for y up to 0.042). By taking into account the effect of strain in $GaAs_{1-x}N_x$, we deduce that this value is close to the calculated difference between the band gaps of $In_yGa_{1-y}As$ and GaAs which is near 50 meV at y=0.042. This also confirms that the effect of indium and nitrogen on the host states can be separated. [1] Turcotte et al., J.Vac. Sci. Technol. A 22, 776 (2004). [2] Shtinkov et al., Phys. Rev. B 67, 081202R (2003).

9:00 AM EE11.4
Abstract Withdrawn

9:15 AM EE11.5
Optical Properties of GaAsN Quantum Structures. Ting Liu[1], Sandeep Chandril[2], Thomas H. Myers[2] and Dimitris Korakakis[1]; [1]Department of Computer Science and Electrical Engineering, West Virginia University, Morgantown, West Virginia; [2]Department of Physics, West Virginia University, Morgantown, West Virginia.

GaAsN has attracted a lot of interest because of its long wavelength application in optoelectronic devices. To date, most quantum dots (QD) studies involving GaAsN have involved InAs QDs with a GaAsN overlay to reduce strain. We have developed GaAsN quantum dot-like structures grown on (100) GaAs substrates by Molecular Beam Epitaxy. Atomic force microscopy (AFM), photoluminescence (PL), Auger Electron Spectroscopy (AES) and Scanning Electron Microscopy (SEM) are used to study how the structure of GaAsN and nitrogen composition influence the optical properties of these QD. The standard deviation of the quantum dot size is correlated with the full-width-half-maximum (FWHM) of the PL. Nitrogen content plays an important role on the properties of the GaAsN. By varying the flow rate of the RF-nitrogen plasma, we also investigated the influence of nitrogen. AES was used to estimate the nitrogen content. The dot dimensions as related to the nitrogen contained will be demonstrated. Our study will also show the effect of nitrogen composition on the wavelength. Too little or too much nitrogen all lead to a blue shift of the wavelength because too much nitrogen contributes to the deterioration of the quality of the sample. This work is supported by NSF 0102753.

9:30 AM *EE11.6
GaNAsBi Semiconductor Alloy with Temperature-Insensitive Bandgap. Masahiro Yoshimoto, Wei Huang, Gan Feng and Kunishige Oe; Kyoto Institute of Technology, Kyoto, Japan.

The authors have been investigating Bi-containing semiconductor alloys to create a new semiconductor with a temperature-insensitive band gap. Recently, a new semiconductor alloy $GaN_yAs_{1-x-y}Bi_x$ has been successfully grown by molecular beam epitaxy (MBE). The $GaN_yAs_{1-x-y}Bi_x$ grown layers lattice-matched to GaAs emitted room-temperature photoluminescence (PL) at an infrared region including waveband for optical fiber communication. Since the temperature coefficient of the PL peak energy was measured to be much smaller than that of InGaAsP, $GaN_yAs_{1-x-y}Bi_x$ is suitable to realize a new semiconductor laser diode with a temperature-insensitive wavelength for optical fiber communication light sources. The new laser diode will eliminate the use of massive temperature-control equipment in wavelength-division-multiplexing (WDM) fiber communication systems. In this paper, growth and photoluminescence (PL) characteristics of $GaN_yAs_{1-x-y}Bi_x$ are overviewed. Growth conditions to achieve Bi incorporation into the epilayer and a related growth mechanism are discussed. Effects of Bi and N incorporation on PL peak energy and its temperature coefficient of $GaN_yAs_{1-x-y}Bi_x$ are discussed quantitatively. $GaN_yAs_{1-x-y}Bi_x$ was grown on (001)-oriented GaAs substrate in MBE with solid sources of Ga, As and Bi. Activated nitrogen generated from N_2 gas in rf plasma was used as the nitrogen source. $GaN_yAs_{1-x-y}Bi_x$ layer was grown at substrate temperature in the range between 350 and 380 °C. The GaBi and GaN molar fractions were evaluated by Rutherford back scattering (RBS) measurements and secondary ion mass spectroscopy (SIMS), respectively. The lattice-matching of $GaN_yAs_{1-x-y}Bi_x$ to GaAs was confirmed by X-ray diffraction measurements on a series of $GaN_yAs_{1-x-y}Bi_x$ with various GaBi and GaN molar fractions. The alloy was found to be lattice-matched to GaAs in the form of $Ga(N_{0.33}Bi_{0.67})_zAs_{1-z}$. The $GaN_yAs_{1-x-y}Bi_x$ grown layer emitted PL at room temperature. Its PL peak energy shifted to a longer wavelength with increasing GaBi and GaN molar fractions with the red shift coefficients of $\sim$62 meV/%Bi and $\sim$130meV/%N, respectively. The temperature dependence of the PL peak energy of $GaN_yAs_{1-x-y}Bi_x$ in the temperature range of 150-300K is very close to that of $GaAs_{1-x}Bi_x$ with the same GaBi molar fraction and decreased with increasing GaBi molar fraction in $GaN_yAs_{1-x-y}Bi_x$. This indicates that the temperature coefficient is governed by the GaBi molar fraction and is irrelevant to the GaN molar fraction. The temperature coefficient of the PL peak energy for $GaN_yAs_{1-x-y}Bi_x$ is 1/3 of the temperature dependence of the bandgap for GaInAsP alloy. Because lattice matching and PL emission in the optical fiber communication waveband are realized simultaneously, $GaN_yAs_{1-x-y}Bi_x$ is very promising for the fabrication of a laser diode with a temperature-insensitive emission for WDM communication systems.

10:30 AM *EE11.7
GaInNAsSb Long Wavelength Lasers, Solar Cells and Photonic Integration. James S. Harris, Solid State and Photonics Lab, Stanford University, Stanford, California.

The incredible growth of the Internet and data communications is pushing the bandwidth requirements for fiber networks and expansion of metro and local area networks at an unprecedented pace. Low cost lasers which are easily packaged and coupled to fiber are needed for the next generation of these networks. Fiber Raman and semiconductor optical amplifiers which expand the bandwidth across the entire low loss region are also required. GaInNAsSb is a promising new active layer material that can be grown on GaAs to achieve 1300-1600nm emission for both high speed, low cost VCSELs, SOAs and high power Raman pump lasers. The successful development of GAInNAs(Sb) has also attracted attention for 1.0 eV bandgap solar cells because the highest efficiency cells are currently stacked cells on Ge, but there was previously no lattice matched 1.0 eV alloy to Ge.

This materials system provides many epitaxial growth challenges as the equilibrium phases of the constituent binary alloys are cubic (GaAs and InAs) and hexagonal (GaN and InN) and the material easily phase segregates with increasing N and In compositions. In addition to the growth challenges, GaInNAs(Sb) is different from other III-V alloys in that its bandgap decreases with a decrease in lattice constant and it exhibits an interesting N nearest neighbor annealing effect. Because of the five elements GaInNAs(Sb) offers a broad range of bandgap and strain engineering possibilities, including a more favorable conduction band/valence band offset division which provides greater confinement of electrons, resulting in higher temperature and power capabilities for GaInNAs(Sb) lasers. We have achieved record low threshold current density in 1500nm edge emitting lasers and the first monolithic 1450nm VCSEL on GaAs. In addition to the laser performance, this alloy is enabling integration of higher efficiency, multi-bandgap stacked junction solar cells and photonic crystal structures for waveguides, high Q cavities and other passive components that will be crucial for increased levels of integration in photonic circuits. The recent progress in both materials growth and devices will be described.

11:00 AM EE11.8
MBE Growth and Optoelectronic Properties of Dilute $GaN_yAs_{1-x-y}Bi_x$ Alloys. Erin C. Young[1], Sebastien Tixier[2], Thomas Tiedje[2,3], Scott Webster[2], Dan Beaton[2], Nikolaj R. Zangenberg[2], Sebastien Francoeur[4], Angelo Mascarenhas[4], Peng Wei[5] and Francois Schiettekatte[5]; [1]Materials Engineering, University of British Columbia, Vancouver, British Columbia, Canada; [2]Department of Physics and Astronomy, University of British Columbia, Vancouver, British Columbia, Canada; [3]Department of Electrical and Computer Engineering, University of British Columbia, Vancouver, British Columbia, Canada; [4]National Renewable Energy Laboratory, Golden, Colorado; [5]Departement de Physique, Universite de Montreal, Montreal, Quebec, Canada.

Isoelectronic co-doping of GaAs with N and Bi has been proposed as a way to alleviate the degradation in electronic properties associated with nitrogen in the dilute alloy GaNAs [1]. In addition co-doping with N and Bi allows access to bandgaps in the near infrared (1.0 - 1.5 um) with relatively small N concentrations as compared to the GaInNAs alloys [2] due to the giant bandgap bowing effect associated with Bi (84 meV/ % Bi). A giant bowing in the spin orbit splitting has also been observed recently in GaAsBi [3]. We have grown $GaAs_xBi_{1-x}$ and $GaN_yAs_{1-x-y}Bi_x$ films by plasma-assisted, solid source molecular beam epitaxy with Bi and N concentrations up to x = 3.1% and y = 1.6%, as determined by Rutherford backscattering and high-resolution x-ray diffraction. The extent of Bi incorporation into GaAs is highly sensitive to the growth conditions, and requires both a low growth temperature (<400C) and an As to Ga flux ratio on the order of 1. At the standard growth temperatures and As overpressures used in GaAs growth, Bi does not incorporate (< $2x10^{17}/cm^3$). Instead it surface segregates and acts as a surfactant. The presence of the Bi surfactant enhances the N incorporation efficiency in GaN_yAs_{1-y} by up to 50%, increases the photoluminescence efficiency and reduces the low temperature PL linewidth. Despite the non-standard growth conditions necessary for Bi incorporation, strong room temperature photoluminescence is observed for the $GaAs_xBi_{1-x}$ and $GaN_yAs_{1-x-y}Bi_x$ films, with emission at 1150 nm for $GaN_yAs_{1-x-y}Bi_x$ lattice matched to GaAs (x = 0.85%, y = 1.4%). In this paper we investigate the relationship between growth parameters, Bi incorporation and optoelectronic properties of dilute bismide and nitride-bismides alloys using photoluminescence and electroreflectance. 1. A. Mascarenhas et al, Superlattices and Microstructures 29 (2001) 395. 2. S. Tixier et al, Appl. Phys. Lett. 86 (2005). 3. S. Yoon, M.J. Seong, B. Fluegel, S. Francoeur, A. Mascarenhas, S. Tixier and T. Tiedje (to be published).

11:15 AM EE11.9
Interdiffused SbN-based Quantum Well on GaAs for 1300-1550 nm Diode Lasers. Ronald Ariwibowo Arif and Nelson Tansu; Center for Optical Technologies, Department of Electrical and Computer Engineering, Lehigh University, Bethlehem, Pennsylvania.

Though InGaAsSbN quantum well (QW) grown by molecular beam epitaxy (MBE) on GaAs have resulted in low threshold laser devices, the pursuit of InGaAsSbN materials system by metalorganic chemical vapor deposition (MOCVD) is still challenging. Here we propose a novel approach to realize InGaAsSbN QW, which allow us to circumvent the challenges present in the MOCVD growth of this quinary compound. Our novel approach combines the already-established MOCVD growth technique of InGaAsN and InGaAsSb QWs, with a post-growth rapid-thermal annealing (RTA) that leads to interdiffusion of Sb and N-species, resulting in high quality *interdiffusedInGaAsSbNQW*. The initial step involves the MOCVD growth of the active region consisting of InGaAsSb and InGaAsN QW layers, where the former is sandwiched by the latter. As the InGaAsN and InGaAsSb QWs are grown in separate layers, optimization of their individual MOCVD growth parameters can be achieved independently. By conducting post-growth RTA, the Sb-N interdiffusion process is allowed to take place resulting in mixed SbN-based QW structure, due to the large disparity of the Sb-N diffusion constants (at annealing temperature of 600°C, the diffusion constant of N-species in GaAs matrix is approximately >150 times than that of Sb-species). We have conducted numerical and experimental works to investigate the interdiffused InGaAsSbN QW for achieving emission wavelength up to 1550-nm regime. Numerical studies indicate emission wavelength up to 1560-nm is achievable by interdiffused InGaAsSbN QW, realized from annealing the as-grown 3-nm $In_{0.4}Ga_{0.6}As_{0.95}Sb_{0.05}$ sandwiched by 2.5-nm $In_{0.4}Ga_{0.6}As_{0.97}N_{0.03}$ layers at a temperature of 600°C for 50 sec. Strain compensated interdiffused SbN-based QW on GaAs can also be achieved by annealing at 600°C for 100 sec the as-grown sample consisting of 2.5-nm $GaAs_{0.965}N_{0.035}$ (tensile) and 6-nm $In_{0.43}Ga_{0.57}As_{0.95}Sb_{0.05}$ (compressive) QW layers, resulting in interdiffused InGaAsSbN QW with emission wavelength up to 1500-nm. Experiments involving RTA and photoluminescence (PL) measurements have also been conducted to understand the fundamental Sb-N diffusion phenomena in GaAs matrix. Annealing of MOCVD-grown 2.3-nm $GaAs_{0.7}Sb_{0.3}$ QW sandwiched by GaAs barriers at 700°C for 100 sec leads to minimal PL blueshift of only ~6 nm. In contrast to that, under similar annealing condition (at 700°C for 100 sec) a much larger blueshift of ~132 nm is observed for the sample consisting of MOCVD-grown 7.3-nm $GaAs_{0.957}N_{0.043}$ QW surrounded by GaAs barriers. These findings indicate the low diffusivity of Sb-species and high diffusivity of N-species in GaAs matrix, in agreement with theory. This finding also provides an indication of the feasibility of the interdiffused SbN-based QW. Experiments on strain-compensated GaAs $_{0.7}Sb_{0.3}$-$GaAs_{0.966}$ $N_{0.034}$ QWs on GaAs will also be conducted to investigate the interdiffused GaAsSbN QW structure for 1300-1550 nm laser active regions.

11:30 AM EE11.10
Growth and Characterization of InGaNAs Quaternary Alloys for the Fabrication of Long Wavelength MSM Photodetectors on GaAs Substrates. Erle Daniel Higgins, Julian Noad, Francois Gouin and Dave Coulas; Optoelectronic Materials and Components, Communications Research Centre, Ottawa, Ontario, Canada.

Dilute nitride III-V materials such as GaNAs and InGaNAs have been the focus of much theoretical and experimental research activity over the last few years. Grown on large-area GaAs substrates, they are ideal candidates for the fabrication of integrated optoelectronic devices that could be monolithically integrated with GaAs based MESFET and HBT circuitry to produce complex multifunction optoelectronic integrated circuits. Potential applications for these dilute nitride materials range from the fabrication of high-speed long wavelength photodetectors suitable for use in metro or WAN communication networks to microwave signal distribution for satcom applications such as large space-based phased array antennas. In this paper, the optical and electrical properties of both as-grown and annealed thick $In_xGa_{1-x}N_yAs_{1-y}$ layers grown by metal organic chemical vapour deposition (MOCVD) are presented. Through careful control of the Trimethylindium (TMIn), Dimethylhydrazine (DMHy), Trimethylgallium (TMGa) and Arsine (AsH3) precursors, lattice matching conditions were achieved for epitaxial layers containing approximately 3% nitrogen and 11% indium with bandgap wavelengths to 1.3 μm. Nomarski optical microscopy and double crystal x-ray diffraction (XRD) measurements have been used to confirm material quality and lattice-matched conditions. Low temperature (10K) photoluminescence scans were performed. It was found that there was little or no PL from as-grown layers; alloy activation through rapid thermal annealing was required to obtain observable photoluminescence peaks. Similarly, Hall measurements on the thick layers also required activation to show average carrier concentrations of $5.5x10^{17}$ cm^{-3} and mobility of 50 cm^2/Vs. The DC and frequency response performance characteristics of Metal-Semiconductor-Metal (MSM) photodetectors fabricated on both as-grown and annealed InGaNAs materials are examined and compared to similar structures fabricated using GaAs and InGaAs/InP epitaxial materials.

11:45 AM EE11.11
Impurity and perturbed host states in III-V semiconductors containing N and Bi*. Yong Zhang[1], Angelo Mascarenhas[1] and Lin-Wang Wang[2]; [1]National Renewable Energy Lab, Golden, Colorado; [2]Lawrence Berkeley National Laboratory, Berkeley, California.

It is well-known that N or Bi doing in III-V semiconductors may generate a number of impurity states and lead to perfound modifications of the host band structure. We have performed electronic structure calculations for both III-V:N and III-V:Bi, using first-principles pseudopotential based charge patching techniques[1-3]. We will address the following issues: (1) How accurately can the

modern band structure calculation techniques calculate the enregy level of the impurity and the energy shift of the perturbed host state? (2) How does one distinguish impurity states from perturbed host states or vise versa in a supercell calculation? (3) What are the similar and dissimilar aspects between III-V:N and III-V:Bi? In addition, other effects related to the isoelectronic impurity incorporation will be discussed (e.g, a giant enhancement of the spin-orbit interaction in GaAs:Bi)[3]. Comparisons with the availabe most accurately measured experimental results[2,4] will be presented. * yong_zhang@nrel.gov 1. L. W. Wang, Appl. Phys. Lett. 78, 1565 (2001); L. W. Wang, Phys. Rev. Lett. 88, 256402 (2002). 2. Y. Zhang, et al., Phys. Rev. B 68, 075210 (2003). 3. Y. Zhang, A. Mascarenhas, and L. W. Wang, Phys. Rev. B 71, 155201 (2005). 4. S. Francoeur, et al., Appl. Phys. Lett. 82, 3874 (2003); B. Fluegel, et al., Phys. Rev. B (2005). Work supported by DOE.

SESSION EE12: Advanced Dielectrics and Si-Based Materials

Chair: Matthew Erdtmann
Thursday Afternoon, December 1, 2005
Constitution B (Sheraton)

1:30 PM EE12.1
The Microstructures at the Interfaces of LaScO3 / Si.
Fude Liu[1], Lisa Edge[2], Darrell G. Schlom[2] and Gerd Duscher[1,3]; [1]Department of Materials Science and Engineering, NC State University, Raleigh, North Carolina; [2]Department of Materials Science and Engineering, Penn State University, University Park, Pennsylvania; [3]Condensed Matter Division, Oak Ridge National Lab, Oak Ridge, Tennessee.

Aggressive down scaling of CMOS devices requires the introduction of new and alternative insulation materials to replace SiO2. The extremely high dielectric constant of Perovskite-type metal oxides (ABO3) makes them an obvious candidate. A good interface for this application requires either that the ABO3 is amorphous, or that it is single-crystalline with a low density of dangling bonds between it and the silicon substrate. Amorphous ABO3 is expected to be able to adjust its local bonding and reduce the silicon dangling bonds at the interface. However, these ionic materials must be kept amorphous even after post-deposition high-temperature processing in order to maintain a sharp interface and avoid possible additional leakage along grain boundaries. In this study, Z-contrast imaging, EELS and HRTEM have been applied to study the interfaces of the LaScO3/Si system. Without heat treatment, LaScO3 thin film is amorphous and the interface between it and underlying silicon is sharp. Heat treatment above 700 degree C resulted in recrystallization of the LaScO3. Additionally, all samples showed an amorphous intermediate layer, which is La deficient as verified by EELS results. There is only a trace of silicon oxygen bonding present at the interface of this La deficient layer and the crystalline Si. The amount of this oxide bonds is consistent with a monolayer of Si atoms bonded to the intermediate oxide layer. We conclude on an atomistically sharp interface with an intermediate amorphous layer with presumably lower dielectric constant. Keywords: High dielectric constant; Perovskite; Interface; Z-contrast imaging; EELS; HRTEM Acknowledgement This work has been funded by the National Science Foundation under contract number DMR 0244724 and the U.S. Department of Energy under contract number DE-AC05-00OR22725.

1:45 PM EE12.2
Deposit nitrided HfO2 films in O2 or N2O. Qian Luo, William Rees and Dennis Hess; Georgia Institute of Technology, Atlanta, Georgia.

Nitrided HfO2 films are deposited by direct liquid injection chemical vapor deposition (CVD) using O2 or N2O as oxidants. Deposition kinetics, phase, chemical composition, bonding, and dielectric properties of the films obtained from the two different oxidants are compared. Depositions in nitrous oxide display an activation energy (9.9 kcal/mol) less than that observed with oxygen (13.6 kcal). Films obtained from nitrous oxide are amorphous as determined by Grazing Incidence X-ray diffraction (GID), while films deposited using oxygen are mixtures of amorphous and crystalline phases. Films deposited from nitrous oxide have lower bulk and interface (with silicon) nitrogen concentrations relative to films deposited in oxygen. The amorphous structure of nitrous oxide deposited films and an enhanced concentration of oxygen atoms from nitrous oxide are believed to be the reasons for the reduced interface nitrogen concentrations. Capacitance - voltage (C-V) measurements demonstrate that films deposited with nitrous oxide have lower dielectric constants and lower interface trap densities relative to films deposited from oxygen. Leakage currents of the films deposited in nitrous oxide are smaller than those of films deposited in oxygen. Nitrogen concentration at the film/silicon substrate interface is appears to be the reason for the distinct electrical properties of films deposited using the two oxidants.

2:00 PM EE12.3
Direct detection of electrons with wide energy range using a fully-depleted delta-doped high purity silicon p-i-n diode array. Shouleh Nikzad[1], Thomas J. Cunningham[1], Ronald P. Ruiz[1], David M. Soules[1] and Steve E. Holland[2]; [1]Jet Propulsion Laboratory, Pasadena, California; [2]Lawrence Berkeley National Laboratory, Berkeley, California.

Direct detection of electrons in the 0.1 keV to 20 keV energy range has been demonstrated using a delta-doped high purity silicon p-i-n diode array. Full depletion of high purity detectors allows the detection of all electrons and allows the determination of device gain as a function of the incident energy, as well as an accurate measurement of silicon quantum yield at low energies. We have developed a low-temperature process for forming highly thin electrodes on the p-type substrate of fully depleted fully fabricated high purity silicon pin diode arrays. This electrode is transparent to shallow-penetrating ionizing radiation. The electrode is formed by growth of a boron delta layer using molecular beam epitaxy on the back surface of the fully processed device. In this talk, we will discuss the device structure, processing, and characterization methods used to demonstrate the direct detection of low-energy electrons.

2:15 PM EE12.4
Ultra-low temperature growth of Antimony delta-doped Silicon on high-purity Imaging Detectors. Jordana Blacksberg[1], Michael Hoenk[1], Shouleh Nikzad[1] and Steve Holland[2]; [1]Caltech Jet Propulsion Laboratory, Pasadena, California; [2]Lawrence Berkeley National Laboratory, Berkeley, California.

We have developed a low temperature process for Sb delta-doping of silicon which can be used to form a thin back-surface contact for back-illuminated high purity n-type imaging detectors. Non-equilibrium growth by Molecular Beam Epitaxy (MBE) is used to achieve very high dopant incorporation in a thin, surface-confined layer. Optimization of this process has enabled the growth of a delta-doped layer with $>10^{14}$cm^{-2} antimony. The temperature is kept below 450 °C throughout the entire process, which is required for compatibility with fully processed and functional Al-metallized devices. High purity silicon detector arrays, under development at LBNL for broadband detection, can be fully depleted up to a thickness of few hundred microns with the application of a modest voltage. Full depletion enables high-resolution imaging, while greater device thickness extends the spectral response farther into the infrared (i.e., 200 μm thick devices can detect wavelengths up to $\sim$1 μm limited by low absorption near the silicon bandgap). However, full depletion also makes these devices particularly susceptible to surface effects. Surface states at the back surface of an unpassivated, fully-depleted device cause an unacceptably high leakage current. The back electrode of high purity devices must therefore perform a dual function. It must provide a conductive back electrode, and it must passivate the surface to prevent excess dark current. In addition to performing these functions, a delta-layer will have the added benefit of having a high transparency to shallow-penetrating radiation, which results in a significantly higher detection efficiency compared to the relatively thick electrodes fabricated by conventional processes. For example, delta-doped CCDs detect UV photons and low energy particles with high efficiency, despite the fact that most of the absorption takes place within a few nanometers of the silicon surface. We have applied our process to high purity n-type p-i-n photodiode arrays and Charge Coupled Devices (CCDs), and have successfully imaged with MBE-modified CCDs biased above full depletion. Dark current is shown to be as low as other state-of-the art processes indicating excellent surface quality. We will discuss the effects of growth conditions on the leakage current and quantum efficiency of these detectors. We will report on our most recent quantum efficiency measurements with the delta layer placed at various distances from the back of the CCD. These results show that quantum efficiency improves (especially in the near ultraviolet) as the Sb-doped layer is placed closer to the back surface.

2:30 PM EE12.5
Optimization of SiGe Graded Buffer Defectivity and Throughput by Means of High Growth Temperature and Pre-Threaded Substrates. Matthew Erdtmann[1], Matthew T. Currie[1], Joseph C. Woicik[2] and David Black[2]; [1]AmberWave Systems Corporation, Salem, New Hampshire; [2]National Institute of Standards and Technology, Gaithersburg, Maryland.

The SiGe relaxed graded buffer allows for the realization of strained Si, strained Si on insulator (SSOI), and monolithic integration of optoelectronics on Si. To be inserted into production, it must be both low-defectivity and economical. For the former, a reduction of the threading dislocation density (TDD) to tolerable levels and an elimination of dislocation pile-ups are needed. For the latter, the

graded buffer thickness and growth time must be minimized, so that the throughput approaches that of Si homoepitaxial wafers. To date these objectives have been mutually opposed, since the defectivity of a graded buffer is inversely dependent on growth rate and grade rate. In this work, we employ $GeCl_4$ to grow at temperatures above 1000°C where extremely high dislocation glide velocities are available. First, SiGe graded buffers were grown with varying growth rates and grade rates on prime Si substrates. Etch pit density measurements exhibited a mild sensitivity of the TDD and dislocation pile-up density (DPD) to the grade rate, but a complete independence to the growth rate. We show that, in the high-temperature growth regime, relaxation is not dislocation-glide limited but rather dislocation-blocking limited. Thus, further changes to the graded buffer growth conditions will not result in dramatic lowering of the TDD, since the path length traveled by a gliding dislocation is essentially fixed. However, for a specific TDD, the growth rate can be increased radically to improve the graded buffer throughput. Second, single SiGe layers with varying relaxation on both prime Si substrates and "pre-threaded" Si substrates (TDD = 10^2-10^5 cm^{-2}) were grown. By use of x-ray topography and Nomarski microscopy, we demonstrate that a paucity of substrate threading dislocations spurs immediate heavy dislocation bundling from the substrate edge, leading to localized relaxation. Dislocation bundling increases the dislocation blocking strength and facilitates the formation of dislocation pile-ups. Growing on pre-threaded substrates eliminates dislocation bundling and allows for globally uniform relaxation from the onset. Third, SiGe graded buffers were grown with varying grade rates on both prime and pre-threaded Si substrates. Because dislocation bundling is eliminated, dislocation pile-ups are virtually eliminated—even for grade rates up to 50% Ge/μm. We therefore demonstrate, through identification and subsequent reduction of the mechanism responsible for limiting relaxation during graded buffer epitaxy, that SiGe graded buffers can be grown both economically—actual throughputs of over 10 wafers per hour for 20% SiGe relaxed graded buffers—and with low defectivity levels—TDD = 7×10^4 cm^{-2} for a 2% Ge/μm grade rate to 2×10^5 cm^{-2} for a 50% Ge/μm grade rate and DPD $\sim 10^{-2}$ cm^{-1}. Not only can this work abet the realization of SiGe-based applications, including strained Si and SSOI, but it can be readily applied to other material systems as well.

3:15 PM EE12.6
Low-energy Electron Microscopy Investigations of Elastically Strain Relaxed Silicon/Germanium Nano-Membranes.
Chanan Euaruksakul, Michelle M. Roberts, Donald E. Savage and Max G. Lagally; Materials Science and Engineering, University of Wisconsin-Madison, Madison, Wisconsin.

We have developed a process to fabricate free-standing membranes made of layers of Si and SiGe that are elastically strain relaxed, so that we can in principle make strained Si without dislocations or threads. Such materials could be superior for hi-speed semiconductor devices. The membranes are made by chemical vapor deposition (CVD) of SiGe alloy and Si layers on silicon-on-insulator (SOI) substrates and then released with hydrofluoric acid (HF). Formation of dislocations is kinetically limited by the growth temperature during CVD. After the films are released from SOI substrates and form elastic strain sharing structures, [1] no new dislocations are created. In this study, low-energy electron microscopy (LEEM) was used to observe in real time dislocations in membranes before and during thermal annealing. The results show that, after the thermal annealing, the density of dislocations on released membranes is substantially lower than on identical film structures grown on SOI substrates but not released. The results demonstrate that the dislocation-free membrane structures are thermodynamically stable, confirming the conclusions previously drawn from x-ray diffraction, [1] but extending them to much lower dislocation densities. [1] M. M. Roberts, D. E. Savage, and M. G. Lagally, submitted. Research supported by NSF, DOE, and AFOSR

3:30 PM EE12.7
Franz-Keldysh Effect in Strained Ge on Si for Light Modulation. Samerkhae Jongthammanurak[1], Jifeng Liu[1], Douglas Cannon[1], David Danielson[1], Ching-yin Hong[1], Dong Pan[1], Kazumi Wada[2,1], Jurgen Michel[1] and Lionel Kimerling[1]; [1]Materials Science and Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts; [2]Materials Engineering, The University of Tokyo, Tokyo, Japan.

Silicon-based modulators are important building blocks for complementary-metal-oxide-semiconductor (CMOS) compatible optoelectronics integrated circuits (OEICs). Until now, few silicon-based modulators with modulation speed above a gigahertz have been demonstrated. These modulators, however, rely on charged-carrier effect with an intrinsic drawback of long carrier lifetime that limits the modulation speed. To overcome this limitation, we propose a Si-based device based on the electro-absorption effect of strained Ge on Si. This field-effect modulation has the potential to achieve > 40gigahertz modulation speeds. Germanium is a promising candidate in group IV materials for field-effect modulation, utilizing the so called Franz-Keldysh effect, due to the relatively small difference (0.14eV) between its direct and indirect band gap. In other word, Ge can be considered as a pseudo direct band gap material. Therefore, the presence of an electric field significantly enhances the absorption at energies smaller than the direct gap. Due to the thermal expansion mismatch between the Ge epitaxial film and Si substrate, 0.2% tensile strain has been introduced into our Ge films, which further decreases the difference between the direct and indirect band gap of Ge. The Franz-Keldysh effect in 0.2% strained Ge on Si substrate has been modeled and experimentally characterized in this paper. From the modeling, an electric field of 70kV/cm increases the absorption coefficient at 1645nm from 57 cm-1 to 230 cm-1, having the potential to achieve a 9 dB extinction ratio with a 3 dB insertion loss from a 120 micron-long electro-absorption modulator device. In our measurements, we observed a field-induced absorption enhancement in the tensile strained Ge/Si p-i-n diodes. We measured spectral responsivities under different reverse voltages and extracted spectral absorption coefficients. Under an electric field of 70 kV/cm, the absorption coefficient at 1645nm significantly increased from 62 cm-1 to 230 cm-1, in a very good agreement with our modeling.

3:45 PM EE12.8
Sn-based Group-IV Semiconductors on Si: New Infrared Materials and New Templates for Mismatched Epitaxy. Jose Menendez[1], Vijay R. D'Costa[1], Candi S. Cook[1], John Kouvetakis[2] and John Tolle[2]; [1]Physics and Astronomy, Arizona State University, Tempe, Arizona; [2]Chemistry and Biochemistry, Arizona State University, Tempe, Arizona.

We report on the growth and properties of binary GeSn and ternary SiGeSn alloys on Si substrates. Using a novel CVD approach, high quality GeSn films with up to 20% Sn have been deposited on Si substrates. X-ray studies indicate that the GeSn films are strain-free, and TEM results show that the large lattice mismatch between the film and the substrate is relieved by Lomer dislocations at the interface. The bulk of the films are found to be virtually dislocation free. This material is of great interest due to the predicted cross-over to a direct gap semiconductor for moderate Sn concentrations. We have carried out extensive optical studies, including spectroscopic ellipsometry, to study its electronic structure. We find that the direct band gap, and, consequently, the main absorption edge, shifts monotonically to lower energies as the Sn concentration is increased. The compositional dependence of the direct band gap shows a strong bowing, such that the direct band gap is reduced to 0.4 eV (from 0.8 eV for pure Ge) for a concentration of 14% Sn. The ternary SiGeSn alloy has been grown for the first time on GeSn buffer layers. This material opens up entirely new opportunities for strain and band gap engineering using group-IV materials. In particular, a ternary alloy makes it possible to decouple strain and composition. Our SiGeSn layers have lattice constants above and below the lattice constant of pure Ge, and depending on the thickness and composition of the underlying buffer layer, they can be grown relaxed, with compressive, or with tensile strain. Among the multiple possible applications of this alloy, we show that it is theoretically possible to design multilayer systems containing tensile-strained Ge layers with a strain-induced direct gap. In addition to acting as a buffer layer for the growth of SiGeSn, we have found that GeSn can act as a template for the subsequent growth of a variety of materials, including SiGe and III-V semiconductors. Several examples are shown demonstrating the excellent quality of these materials.

4:00 PM EE12.9
Minority Carrier Lifetime Measurement in Germanium on Silicon Heterostructures for Optoelectronic Applications.
Josephine J. Sheng[1,2] and Malcolm S. Carroll[1]; [1]Sandia National Laboratories, Albuquerque, New Mexico; [2]University of New Mexico, Albuquerque, New Mexico.

Demand for low cost and high density near infrared (NIR) detection has motivated the development and use of germanium on silicon (Ge/Si) heterostructures to extend the optoelectronic application of Si technology. Ge/Si structures are currently being considered for NIR p/n detectors that may be integratable with Si CMOS [1], as well as potentially allowing direct heteroepitaxy of GaAs on Si for laser and solar cells. A common challenge to this technology is the minimization and monitoring of dark current inducing defects that may form in the Ge due to the lattice mismatch with the Si substrate. Various techniques are under development to minimize these defects, which include relaxed buffer layers, and Ge on insulator methods (e.g., wafer bonding), however, most of these are not easily integrated with standard Si CMOS processing. Recently Ge(p)/Si(n) diodes that include the interface in the junction were reported to produce detectors with useful NIR performance despite the defective interface (e.g. J_d=10-15 mA/cm^{-2}, responsivity at 1550 nm = 0.75 A/W, and 200 ps response time), while having the advantage of being easier to

integrate with other Si devices [2,3]. Two critical parameters for the performance of such Ge/Si detector structures are the interface recombination velocity and Ge bulk recombination lifetime, which should be as slow as possible to minimize dark current generation and maximize quantum efficiency. In this paper, we report measurements of the minority carrier lifetime in recrystallized amorphous-Ge (a-Ge) on Si, which is undertaken to examine optimal recrystallization parameters and evaluate the potential of these Ge/Si structures for detectors. Layers of a-Ge from 1 to 400 nm were deposited on Si 150 mm, p-type (2-50 ohm-cm), (100) substrates using plasma enhanced chemical vapor deposition at ~350°C. Samples were then capped with an oxide and rapidly thermally annealed between 450-1050°C in a nitrogen ambient. The minority carrier lifetime of each sample was measured using an inductively-coupled, contactless, photoconductance set-up that measures the agglomerate lifetime of the bulk Si, heterostructure and surfaces. Bulk Si substrate lifetimes were obtained independently before deposition and the surface recombination at the Ge or Si surfaces is suppressed through use of hydrogen termination obtained with a 1:100 HF dip, which thereby allows an effective Ge recombination velocity to be extracted. The effective Ge recombination velocity is the combined recombination from the interface and bulk Ge contributions. It is found that the effective heterostructure lifetimes are sensitive to both the growth and annealing conditions and that effective recombination velocities for the Ge layer can be reduced to as slow as $5\text{-}10\times10^{2}$ cm/s. This value is promising compared to 10^{6} cm/s, which was estimated previously [1]. [1] G. Masini, et al., TED, 48 ('01) [2] S. Fama, et al., APL, 81 ('02) [3] G. Masini, et al., APL, 80 ('02)

4:15 PM EE12.10

T-P Phase Diagram for the Epitaxy of 3C-SiC on Si(001).
Maki Suemitsu[1], Yuzuru Narita[1], Atsushi Konno[1] and Hideki Nakazawa[2]; [1]CIR, Tohoku University, Sendai, Japan; [2]Faculty of Science and Technology, Hirosaki University, Hirosaki, Japan.

To construct ubiquitous-network (or ambient-intelligence) society using well-established Si technology, Si devices must acquire a new ability to "communicate" with various circumstances, via new carriers of information such as bio-materials, photons, environmental chemicals, and mechanical deformations. Ultrathin cubic SiC layer on Si (3C-SiC/Si) has a high potential in this respect, in that SiC is highly bio-friendly, a polar material compatible as a substrate for direct-gap compound semiconductors, wide-gap in its electronic structure, chemically inert, and of considerable mechanical strength. We have been investigating the gas-source (GS)MBE of 3C-SiC/Si using an organosilane(OS) as a single precursor, and have developed the following techniques: (1)OS-buffer method that allows formation of the interfacial buffer layer at 650°C[1], 400°C below the conventional carbonization method, (2)OS-GSMBE method that allows qualified growth of 3C-SiC/Si at 900°C[2], 350°C below the conventional CVD method using SiH_4 and propane, and (3)OS-single-domain method that allows formation of a single-domain 3C-SiC(001)-2×1 surface on a layer as thin as 0.1 μm[3], which is compared to the previous requirement of 5 μm. In epitaxy processes using hydride-source gases like organosilanes, surface hydrogen plays a crucial role. Although surface hydrogen can be a useful surfactant or a template to control the growth, it in many cases acts as an unwanted site-blocker that makes the surface inert against adsorption of source-gas molecules and suppresses the surface migration of adatoms, deteriorating the quality of the grown film. We have in this work conducted a series of OS-GSMBE experiments on 3C-SiC/Si(001) under various monomethylsilane pressures (P) and substrate temperatures (T), and have obtained, by using FTIR and AFM evaluations, a kind of a T-P phase diagram on the quality of the film. As a result, good epitaxy was found to realize when $P_{c1}(T) < P < P_{c2}(T)$ holds. Here, $P_{c1}(T)$ and $P_{c2}(T)$ are a pair of critical pressures, and each of them is an increasing function of T. P_{c1} corresponds to a pressure below which considerable Si outdiffusion onsets from the Si substrate, forming voids underneath the interface. P_{c2} corresponds to a pressure above which the surface hydrogen coverage becomes too abundant, causing degradation of grown films. We found that the functional form of $P_{ci}(T)$ is best given by an equi-hydrogen-coverage curve, obtained from a balance between the increase of the surface hydrogen coverage due to source-gas adsorption and the decrease by thermal desorption of hydrogen molecules. References [1]H. Nakazawa, M. Suemitsu, and S. Asami, Materials Science Forum 338-342 (2000) pp.269-272. [2]H. Nakazawa and M. Suemitsu, Appl. Phys. Lett., 79(2001) pp.755-757. [3]H. Nakazawa and M. Suemitsu, J. Appl. Phys., 93(2003) pp. 5282-5286

4:30 PM EE12.11

Chemical Vapor Deposition and Defect Characterization of Silicon Carbide Epitaxial Films.
Yi Chen[1], Govindhan Dhanaraj[1], Michael Dudley[1] and Hui Zhang[2]; [1]Materials Science and Engineering, Stony Brook University, Stony Brook, New York; [2]Mechanical Engineering, Stony Brook University, Stony Brook, New York.

Silicon carbide (SiC) is an important semiconductor material used in high power, high frequency and high temperature applications because of its unique combination of properties such as high breakdown field, high electron velocity and high thermal conductivity [1-3]. The wide bandgap of SiC results in a low leakage current even at high temperatures. Epitaxial growth based on chemical vapor deposition (CVD) is commonly used in fabricating these device structures. However the defects nucleated during the growth such as hollow core and closed core dislocations as well as polytype inclusions can limit the device performance. We have developed a sophisticated CVD system aiming at understanding SiC growth kinetics and defect nucleation mechanisms during epitaxial deposition. The hot-zone for the CVD chamber has been designed and fabricated with the aid of temperature simulation using numerical modeling. Epitaxial films have been grown on SiC substrates using propane and silane/silcon tetrachloride as precursor gases and hydrogen/argon as a carrier gases. The growth was carried out at around 150 Torr pressure in the temperature range of 1400-2000°C. Growth rate and morphology of the epitaxial films have been studied using scanning electron microscope, Nomarski optical microscope, atomic force microscope and high resolution X-ray diffraction techniques. The details of the growth and characterization results will be presented. References: 1. Lebedev, A.A. and Chelnokov, V.E., Wide-gap Semiconductors for High-power Electronics, Semiconductor, 33, 999-1001, 1999. 2. Carter, Jr., C.H., Tsvetkov, V.F., Glass, R.C., Henshall, D., Brady, M., Muller, St.G., Kordina, O., Irvine, K., Edmond, J.A., Kong, H.S., Singh, R., Allen, S.T. and Palmour, J.A., Progress in SiC: from Material Growth to Commericial Device Development, Mater. Sci. Eng., B61-62, 1-8 1999 3. G. Dhanaraj, X.R. Huang M. Dudley, V. Prasad and R.H. Ma, chapter 6, p181-232 in "Crystal Growth Technology", Eds K. Byrappa, T. Ohachi, William Andrew co-published with Springer, NY 2003

4:45 PM EE12.12

High-Speed and High-Quality Epitaxial Growth of 6H-SiC by Closed Sublimation Method.
Tomohiko Maeda[1], Yoshihiro Nakamura[1], Motoaki Iwaya[1], Satoshi Kamiyama[1], Hiroshi Amano[1], Isamu Akasaki[1], Tomoaki Furusho[2], Hiroyuki Kinoshita[2] and Masahiro Yoshimoto[3]; [1]Meijo University, Nagoya, Japan; [2]SiXON Ltd., Kyoto, Japan; [3]Kyoto Institute of Technology, Kyoto, Japan.

Thick and high-quality SiC epilayers are indispensable for the high-power SiC-based electron devices with high breakdown voltage. It is known that a closed sublimation method enables us to grow SiC epilayers with high crystalline quality and high growth rate of up to 100 μm/h [1-3]. Therefore, this technique is promising for a mass production of SiC epiwafer and devices with high throughput. In this paper, we report an extremely high speed SiC epitaxial growth by the closed sublimation method, and clarify a correlation between the crystalline quality and growth conditions, such as growth temperature and its gradient. In our experiments, we varied growth rates from 50 to 600 μm/h with changing the growth conditions of the closed sublimation setup. The substrate for the epitaxial growth was Si-face of 6H-SiC (0001) with an off-angle of 2° toward <11-20>. The growth pressure was kept constant at 4 Pa. The growth rate of SiC epi-layer was varied with both the growth temperature and the temperature gradient from the source material to the substrate. We used several sets of graphite susceptors with different temperature gradient. The quality of epilayers was characterized by X-ray diffraction measurement. The full-width-at-half-maximum (FWHM) of X-ray diffraction peak gradually increased with the growth rate, indicating degradation of crystalline quality caused by the high growth rate. After an optimization of the temperature gradient, the high quality SiC epi-layer, whose FWHM of X-ray rocking curve of (0001) diffraction is less than 60 arcsec, was obtained with the growth rate as high as 300 μm/h. While the growth rate is limited to ~20 μm/h for SiC grown by typical chemical vapor deposition(CVD), the high growth of 300 μm/h was achieved in closed sublimation method, indicating feasibility for mass production. This technique may be applicable to the growth for other poly-type crystals such as 4H, 3C and 15R, and valuable to the mass production with high throughput of SiC-based devices. References [1] T. Yoshida, Y. Nishio, S. K. Lilov and S. Nishino, Mater. Sci. Forum 264-268 (1998) 155. [2] T. Yoshikawa, S. Nishino and J. Saraie, Inst. Phys. Conf. Ser. 142 (1996) 57. [3] T. Furusho, S. K. Lilov, S. Ohshima and S. Nishino, Jpn. J. Appl. Phys. 40 (2001) 6737.