SYMPOSIUM Z

Z: Progress in Compound Semiconductor Materials III-Electronic and Optoelectronic Applications

December 1 - 4, 2003

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* Invited paper

SESSION Z1: Low Bandgap/Dilute-Nitride Semiconductors
Chairs: Daniel Friedman and Alexana Roshko
Monday Morning, December 1, 2003
Room 208 (Hynes)

8:30 AM *Z1.1
Effects of Hydrogen on Electronic Properties of Low-Band-Gap Semiconductors. Chris G. Van de Walle, Palo Alto Research Center, Palo Alto, California.

Over the past 20 years we have learnt a great deal about hydrogen in semiconductors, based on experiment as well as theory. The experimental observation that hydrogen can passivate both acceptors and donors, first made in silicon, established its character as an amphoteric impurity. Hydrogen acts as a donor (H^+) in *p*-type material, and as an acceptor (H^-) in *n*-type material, always counteracting the prevailing conductivity. Experiments and first-principles calculations for a number of other semiconductors (including GaAs and GaN) seemed to confirm this behavior as a general feature of hydrogen's interactions with semiconductors. It therefore came as a surprise when calculations showed that hydrogen behaves exclusively as a donor in ZnO [1]. Only H^+ is stable in ZnO, and therefore hydrogen can act as a source of doping, rather than merely reducing the conductivity introduced by other dopants. This unexpected behavior of hydrogen prompted a general investigation of hydrogen in a wide range of materials and of the fundamental mechanisms that govern its electronic behavior. This investigation has resulted in the discovery of a universal alignment of the electronic level of hydrogen [2]. This alignment allows us to predict the electrical character of hydrogen in any material, once some basic information about the band structure is known. The model shows that hydrogen acts as a shallow donor in InN, a prediction that has already been experimentally confirmed [3]. Hydrogen also exhibits very interesting behavior in InGaAsN alloys [4]. Other cases to be discussed include antimonides and SnGe alloys. This work is supported in part by AFOSR and ONR. [1] C. G. Van de Walle, Phys. Rev. Lett. **85**, 1012 (2000). [2] C. G. Van de Walle and J. Neugebauer, Nature **423**, 626 (2003). [3] E. A. Davis *etal.*, Appl. Phys. Lett. **82**, 592 (2003). [4] A. Janotti *etal.*, Phys. Rev. Lett. **89**, 086403 (2002).

9:00 AM Z1.2
Dominant Recombination Processes in GaInNAs/GaAs QW Light Emitting Diodes. Jose M. Ulloa[1], A. Hierro[1], J. Miguel-Sanchez[1], A. Guzman[1], M. A. Pinault[2], E. Tournie[2] and E. Calleja[1]; [1]ISOM-Universidad Politecnica de Madrid, Madrid, Spain; [2]CRHEA-Centre National de la Recherche Scientifique, Valbonne, France.

Laser diodes emitting at the 1.3 and 1.55 μm optical fiber windows based on the GaInNAs/GaAs system have recently been demonstrated. Nevertheless, the threshold current densities remain still high, and the dominant carrier recombination mechanisms limiting light emission in this material system are still unclear. Much information about these mechanisms can be obtained from a detailed analysis of the electroluminescence (EL) of light emitting diodes (LEDs). In this work, GaInNAs/GaAs QW LEDs are characterized by means of I-V, photoluminescence, photocurrent, and EL, as a function of temperature, both for as-grown and rapid-thermal-annealed material, and compared to conventional InGaAs LEDs. The analyzed samples consist of GaInNAs/GaAs SQW p-i-n structures grown by MBE with a N plasma source, with In and N contents in the range of 20-30 % and 1-2.5 %, respectively. At low temperature, the EL shows a transition from a low current region influenced by monomolecular recombination, and related to carrier localization states, to a pure bimolecular radiative recombination region at higher currents. However, carrier localization is found to dominate the emission energy and enhance the external efficiency (ηext) only for small injection currents due to the rapid saturation of the localization states, and leads to a ηext that resembles that of quantum dots. The saturation and relaxation times will be evaluated based on EL pulse time measurements. Higher temperatures lead to a progressive increase of monomolecular recombination through non-radiative recombination centers, which become dominant at room temperature, and do not saturate in the range of considered injection currents. After annealing, a strong increase in ηext is obtained at all temperatures due to the reduction of the density of non-radiative recombination centers. In addition, at low temperature and currents a reduction of the monomolecular recombination saturation current is also observed, whose origin will be discussed.

9:15 AM Z1.3
The effects of atmosphere, temperature, and bandgap on the annealing of GaInNAs. Aaron J Ptak, Sarah Kurtz and Robert C Reedy; National Renewable Energy Laboratory, Golden, Colorado.

GaInNAs lattice-matched to GaAs is a potentially useful material for next-generation, multijunction solar cells. Unfortunately, the material has failed to achieve adequate performance. To help elucidate some of the problems with this material, a large number of doped and undoped samples with bandgaps ranging from 1-1.4 eV have been annealed under various conditions. These conditions include temperatures from 550-700°C, and arsine, dimeric arsenic and nitrogen atmospheres. The solid-source molecular-beam epitaxy (MBE) samples did not contain detectable concentrations of hydrogen or carbon as grown. Annealing the MBE-grown GaInNAs with a bandgap of ~1 eV under 20 sccm of arsine injects hydrogen into the layers at concentrations greater than 10^{19} cm^{-3}. Annealing at 550°C under arsine results in a surface concentration of hydrogen of ~2x10^{19} cm^{-3} that decreases to <10^{18} cm^{-3} at the back surface of the 0.8 μm thick layer. There is less variation in hydrogen from the front to the back surface at an anneal temperature of 600°C, and by 650°C the hydrogen concentration is nearly constant at ~2x10^{19} cm^{-3} throughout the layer. At 700°C, the near-surface hydrogen begins to be desorbed. The hydrogen causes a decrease of the background hole concentration and at high anneal temperatures causes a change from p-type to n-type conductivity, thereby experimentally verifying that hydrogen acts as a donor in GaInNAs. In contrast, annealing in a nitrogen atmosphere with a sacrificial GaAs proximity cap increases the p-type conductivity, while annealing under dimeric arsenic in the MBE system causes the layers to become depleted of carriers. Analysis of spectral photo-response measurements do not indicate measurable minority-carrier diffusion lengths upon anneal (L<0.1 μm). This finding implies that the material quality is still inadequate for photovoltaic devices.

9:30 AM Z1.4
Improvements in Dilute III-V Nitride Semiconductors with a Bi Flux During Growth. Erin C. Young[3], S. Tixier[1], Tom Tiedje[1,4], K. L. Kavanagh[2], A. N. Koveshnikov[2], S. Francoeur[5] and A. Mascarenhas[5]; [1]Physics and Astronomy, University of British Columbia, Vancouver, British Columbia, Canada; [2]Physics Department, Simon Fraser University, Burnaby, British Columbia, Canada; [3]Metals and Materials Engineering, University of British Columbia, Vancouver, British Columbia, Canada; [4]Electrical and Computer Engineering, University of British Columbia, Vancouver, British Columbia, Canada; [5]National Renewable Energy Lab, Golden, Colorado.

Molecular beam epitaxy growth of the dilute nitride alloy GaAsN with a bismuth surfactant is found to increase the nitrogen incorporation, reduce surface roughness and improve the photoluminescence intensity of the grown films. The presence of a full monolayer coverage of Bi on the substrate during growth increases the N content in GaAsN films by up to 40% relative to films grown under otherwise identical conditions. A similar increase in N incorporation in InGaAs is observed through the suppression of structural relaxation in compressively strained InGaAsN quantum wells grown with a Bi surfactant. The Bi flux increases the N incorporation thereby reducing the strain and increasing the thickness for the onset of misfit dislocation formation in quantum wells. In addition a Bi flux increases the room temperature photoluminescence intensity by a factor of 2-3, either through suppression of intrinsic defects or through a reduction in impurity incorporation. Furthermore, postgrowth AFM studies of GaAsN films show large atomic terraces indicative of step flow growth at a growth temperature of 460C whereas in the absence of Bi the growth occurs through island nucleation. At standard growth temperatures for GaAs, InGaAs, and InGaAsN, (400-600 C) and conventional V/III ratios (2-10), Bi does not incorporate into GaAs even when the growing surface is saturated with Bi. However we have succeeded in incorporating Bi into GaAs and GaAsN by reducing the growth temperature to 380 C and reducing the As/Ga flux ratio to unity or slightly less than unity. These films show room temperature photoluminescence. Analogous to N alloying, small concentrations of Bi produce an anomalously large reduction in the bandgap (85 meV/% for Bi compared with ~150 meV/% for N). These results suggest that the dilute quaternary GaAsBiN alloy is a possible alternative to InGaAsN for small bandgap devices, lattice matched to GaAs.

9:45 AM Z1.5
Structural and Optical Characterization of GaNAs Alloys with High N Concentrations Grown by Laser Ablation. Julio G. Mendoza-Alvarez[1], Jairo A. Cardona-Bedoya[1], Lucero Gomez-Herrera[2], Mario H. Farias[3] and J. A. Diaz[3]; [1]Physics, Cinvestav-IPN, Mexico DF, Mexico; [2]Unidad Legaria, CICATA-IPN, Mexico DF, Mexico; [3]CCMC, UNAM, Mexico DF, Mexico.

GaN-based alloys have been the subject of intensive research since the demonstration by Nakamura et al of blue emmiting LED's and diode lasers based on InGaN/AlGaN heterostructures. The GaNAs alloys are suitable to develop semiconductors with band-gap energies (E_g) covering the complete visible spectrum on the GaN-rich side of the alloy. For high N concentrations in the GaNAs alloy, theoretical calculations by Zunger et al show that this ternary alloy presents a very high bowing parameter in such a way that small As

concentrations in a GaN matrix will shift the E_g-values to lower energies from the one of GaN, 3.42 eV. In this work we report on the growth and characterization of GaN_xAs_{1-x} thin films grown using a laser ablation system with a high ultra vacuum chamber and a 248-nm excimer laser. As substrates we used Corning glass slides, GaAs and Si crystals, and the substrate temperature was in all cases 600 °C. Variable N concentration in the films was accomplished changing the N pressure in the growth chamber during the deposition process, in the range 0-110 mTorr. Using XPS we were able to measure the N concentration in the GaNAs films, obtaining a variation from about 1% for a N pressure of 1 mTorr, up to around 67% for a N pressure of 100 mTorr. Structural properties were characterized by X-ray diffractometry (XRD). These diffractograms show the presence of a GaAs phase with a preferential orientation that depends on the type of substrate used; and also, some peaks which we relate to the GaNAs phase. Absorption spectra measured with a spectrophotometer show that the edge of the absorption changes as the N concentration in the films changes. Photoluminescence (PL) spectra taken at low temperatures (15 K) show, for some samples, the characteristic emission of GaAs, and also a broad PL band at higher energies which we associate to the ternary GaNAs alloy. We discuss all of these results in terms of the presence of the ternary alloy GaN_xAs_{1-x}, with variable stoichiometries from low to high N concentrations. *We acknowledge the financial support of Conacyt-Mexico, grant #35079E

10:30 AM *Z1.6
Meyer-Neldel Rule in Semiconductors: Its Consequences for Understanding Thermal Emission Measurements.
Richard S. Crandall, national renewable energy lab, golden, Colorado.

Recent deep-level-transient-spectroscopy (DLTS) measurements on a large variety of InGaAsN and CuInGaSe alloys show thermal emission rate prefactors (ν) from as small as 100 to as large as 10^{+19} s^{-1}. Physically this prefactor should be within a couple of orders of magnitude of 10^{+12} s^{-1}. In this talk show that these seemingly absurd variations are a direct result of ignoring large entropy changes ($\triangle$S) in thermal emission from deep traps. There is sufficient data to show that ln(ν) varies linearly with thermal emission energy (E). This behavior indicates that the emission rates obey the Meyer-Neldel rule (MNR). Fundamentally the MNR indicates a large entropy change on thermal emission from a deep trap and that this large entropy change arises from the many ways that the necessary number of phonons can be assembled to produce a thermal emission. By correctly including these $\triangle$S variations in interpretation of DLTS data, one finds a single value of ν for all emission energies lying along a single MNR line. Applying detailed balance arguments to ν to determine the capture cross section shows a single capture cross section for all data lying on the MNR line.

11:00 AM Z1.7
Electroabsorption of GaInNAs(Sb) Quantum Wells at 1300nm and Beyond. Vincenzo Lordi, Homan Yuen and James S Harris; Solid State and Photonics Laboratory, Stanford University, Stanford, California.

Electroabsorption modulators operating in the telecommunications wavelength range of 1300-1600 nm are important not only for optical fiber communications, but also for use in optical interconnects to replace the electrical lines limiting the future speed of microelectronics. The design of long wavelength optical interconnects allows lower voltage operation as well as seamless integration with optical networking. The novel dilute nitride III-V alloys, GaInNAs and GaInNAsSb, are promising material systems for realizing quantum-well devices on GaAs that operate in this wavelength range. We have studied the electroabsorption properties of GaInNAs and GaInNAsSb quantum wells (QWs) with GaNAs barriers grown in p-i-n diode structures on GaAs. Absorption spectra were measured at various temperatures from 300 K to 26 K, with applied electric fields up to 200 kV/cm. The spectra demonstrated very nice quantum confined Stark effect (QCSE) behavior. At lower applied electric fields, sharp exciton peaks with FWHM around 20nm were clearly observed. At higher fields up to ~150 kV/cm, broadened excitonic resonances were still apparent, even near room temperature. Absorption changes suitable for the fabrication of optical modulators operating at 1300 nm and beyond were measured. Samples were grown by molecular beam epitaxy (MBE), with atomic N supplied by a radio-frequency nitrogen plasma and Sb supplied by a cracked solid source. Growth at 400-425 °C was followed by rapid thermal annealing at 720-760 °C for 60 sec. The test device consisted of a GaAs p-i-n diode with a 0.5 μm thick intrinsic region containing the QWs. GaInNAs active regions included up to nine QWs (8 nm thick) with 20 nm barriers; GaInNAsSb active regions contained up to 2 QWs. The GaInNAs composition was ~1.6% N and ~30% In, while the GaInNAsSb was ~3% N, ~2% Sb, and ~40% In. The barriers contained ~2% and ~9% N, respectively.

11:15 AM Z1.8
Analysis of Material Properties of GaNAs(Sb) Grown by MBE. Homan Yuen[1], Seth Bank[1], Mark Wistey[1], Vincent Gambin[1], Wonill Ha[1], James S Harris[1] and Akihiro Moto[2]; [1]Electrical Engineering, Stanford University, Stanford, California; [2]Innovation Core SEI Inc., Santa Clara, California.

The dilute-nitride GaInNAs has been found to optically emit at wavelengths longer than previously thought possible for materials grown coherently on GaAs. Kondow, et al. discovered the addition of nitrogen to GaAs decreases both the overall lattice parameter and the bandgap [1]. This has allowed for the development of lasers at the important telecom wavelength of 1.3 μm. However, attempts to push out to 1.55 μm have not been entirely successful with GaInNAs. Addition of further indium or nitrogen results in severely degraded material quality due to phase segregation or relaxation. In an effort to improve material quality, Wang, et al. discovered that antimony could be used as a surfactant in GaInNAs growth [2]. However, it was discovered that antimony acted as both a surfactant and constituent when used in GaInNAs, forming GaInNAsSb. Until now, devices utilizing GaInNAsSb as the quantum well (QW) material used GaNAsSb as the barrier material [3]. Antimony was used for the barriers because it was also thought it could improve the quality of GaNAs and the QW/barrier interfaces. Although GaInNAsSb has been extensively studied as the quantum well material, there has been little study of GaNAsSb. In this talk, an analysis of GaNAsSb will be presented. The samples analyzed in these experiments were grown by molecular beam epitaxy with nitrogen supplied by a rf plasma source. Incorporation of nitrogen is linearly dependent upon the inverse of the group-III growth rate, so the barrier compositions are determined by the choice of QW composition. A study of different growth parameters, such as varying the arsenic overpressure and substrate temperature will be shown. High-resolution x-ray diffraction, secondary ion mass spectrometry, photoluminescence, and photoreflectance results are presented to analyze the quality, composition, strain, and band offset of GaNAsSb. After analysis, results indicate GaNAs is a better QW barrier material than GaNAsSb. [1] Kondow, et al. Jpn. J. Appl. Phys. 35 (1996) 1273 [2] Wang, et al. Appl. Phys. Lett. 75 (2) (1999) 178 [3] Harris, et al. Semicond. Sci. Tech. 17 (2002) 880

11:30 AM Z1.9
MBE Growth Study of GaAsSbN/GaAs Single Quantum Wells. Liangjin Wu[1], Kalyan Nunna[1], Jia Li[1], Sreenivasa Kothamasu[1], Ward Collis[1], Shanthi Iyer[1], Kevin Matney[2] and K. Bajaj[3]; [1]Department of Electrical Engineering, North Carolina Agricultural & Technical State University, Greensboro, North Carolina; [2]Bede Scientific Inc., Englewood, Colorado; [3]Department of Physics, Emory University, Atlanta, Georgia.

In this work, the growth and properties of GaAsSbN single quantum wells are investigated. The heterostructures were grown on GaAs substrates in an elemental solid source molecular beam epitaxy system with a RF plasma nitrogen source. A systematic study has been carried out to determine the influence of growth parameters such as growth procedure, growth temperature and nitrogen pressure on the structural and optical properties of the layers. The layers were characterized using a variety of techniques, namely, in-situ monitoring RHEED, ex-situ PL, XRD and AFM. A significant increase in PL intensity with a corresponding blue shift in emission energy and a decrease in full width at half maximum (FWHM) has been observed on annealing the sample in a nitrogen ambient at 700°C. PL emission wavelengths in the range of 1.25 μm to 1.57 μm at 10K have been obtained on annealed samples.

11:45 AM Z1.10
Growth and characterization of GaPAsN on Si. J. F. Geisz[1], Jerry M Olson[1], W. E. McMahon[1], Th. Hannappel[2,1], K. Jones[1], H. Moutinho[1] and M. Al-Jassim[1]; [1]Nationa Renewable Energy Laboratory, Golden, Colorado; [2]Hahn-Meitner-Institut, Berlin, Germany.

The dilute nitrogen alloy GaPAsN can be lattice matched to silicon with band gaps ranging from 2.3 eV to less than 1.7eV making it of special interest to photovoltaic applications. We have studied the growth and structural quality of the alloy grown on vicinal (001)Si and (001)GaP substrates by MOCVD. Using a particular nucleation scheme, we have deposited 1-μm thick layers that are crack-free and exhibit narrow x-ray linewidths. This nucleation process includes a deoxidation step at 1000°C in H_2 followed by the deposition of a 40 nm-thick GaP layer as the substrate is being cooled to 800°C. The alloy is grown at 700°C. With this nucleation process, the FWHM of the (004) x-ray reflection from a $GaP_{1-x}N_x$ epilayer decreases dramatically from ~300 arcsec for x=0 to 24 arcsecs for x = 0.026. The band gap of this alloy is 1.96 eV. In most cases, this is accompanied by reduction of the threading dislocation density as

measured by XTEM. With the addition of As (and more N), the x-ray linewidths tend to increase. For example, for $GaP_{1-x-y}As_yN_x$ (x=0.038, y = 0.128), the band gap decreases to 1.78 eV and the FWHM of the (004) reflection increases to over 100 arcsecs. Optoelectronic properties of these alloys are strongly influenced by the N concentration, similar to that observed with the GaInAsN dilute alloys. The effect of other process variables on the structural and electronic quality of GaPAsN will be presented and discussed.

SESSION Z2: Growth, Structure, and Defects
Chairs: Omar Manasreh and Todd Steiner
Monday Afternoon, December 1, 2003
Room 208 (Hynes)

1:30 PM *Z2.1
Defect Characterization by Laplace Deep Level Transient Spectroscopy. Anthony Ralph Peaker[1], L Dobaczewski[2], I D Hawkins[1] and K Bonde Nielsen[3]; [1]Centre for Electronic Materials, University of Manchester Institute of Science and Technology, Manchester, United Kingdom; [2]Institute of Physics, Polish Academy of Sciences, Warsaw, Poland; [3]Institute of Physics and Astronomy, University of Aarhus, Aarhus, Denmark.

Laplace Deep Level Transient Spectroscopy (LDLTS) provides an order of magnitude higher resolution in separating emission rates compared to conventional DLTS. This moves DLTS from the regime of being a useful fingerprinting tool to one which can provide us with very valuable information probing the detailed physics of defect siting and defect reactions. Although this is at the expense of sensitivity (LDLTS needs about an order of magnitude higher defect concentration than conventional DLTS). LDLTS still retains many of the valuable features of the original technique. In particular it is possible to characterize defects in narrow surface regions, to depth profile and to measure absolute concentrations. In this paper we review some recent results that have been obtained using the technique. The higher resolution enables the effect of the local environment of the defect to be probed. For example in silicon germanium the effect of exchanging a silicon atom for a germanium atom as the nearest neighbour has been measured for a number of well known defects. Because the populations in different configurations can be quantified it is possible to extract site preferences by comparison with the statistically predicted populations ? some examples of this will be given and the possibility of extending the technique to second nearest neighbour populations discussed. LDLTS can be used in conjunction with uniaxial stress to determine defect siting. Because LDLTS enables very small changes in carrier binding energy to be measured by applying uniaxial stress in the <100>, <110> and <111> directions information on the symmetry of a defect can be obtained we have used this to study several common defects in silicon and provide information on their structure. In the case of some defects it is possible to observe alignment under stress at temperatures above the measurement temperature and the subsequent relaxation. This can be quantified in terms of energies for the motion of specific atoms and so in some cases is a measure of the diffusivity on an atomic scale. Hydrogen is a very common impurity in semiconductors and its motion and siting is an important issue in many materials. Using LDLTS on a beam line we have implanted protons at low temperature and observed the evolution of the hydrogen siting in Si, Ge and SiGe. This technique can be applied to many defects in a wide range of materials and is expected to provide new insights into defect reactions in semiconductors over the next few years.

2:00 PM Z2.2
HVPE-based orientation-patterned GaAs: added-value for non-linear applications. David Faye[1], Eric Lallier[1], Evelyne Gil-Lafon[2], Arnaud Grisard[1] and Bruno Gerard[1]; [1]Thales Research & Technology, ORSAY, France; [2]LASMEA UMR CNRS 6602, Blaise Pascal University, AUBIERE, France.

The recent advances in the fabrication of orientation-patterned GaAs (OP-GaAs) offer new opportunities for non-linear optical applications. Thanks to the quasi-phase matching technique, which promotes the use of the high intrinsic quadratic optical non-linearity (χ^2), GaAs structures are now available for the generation of second harmonic, parametric oscillation and amplification over a wide bandwidth [0.9 μm ; 12 μm], exhibiting high efficiency with respect to conventional non-linear cristals such as LN (Lithium Niobate). In this paper, a new route is presented for the development of OP-GaAs for both guided wave and bulk optical applications. It is based on the use of the near-equilibrium growth process HVPE (Hydride Vapour Phase Epitaxy) that enables high quality thick orientation-selective regrowth on OP-GaAs substrates with dimensions fully compatible with targeted applications. Emphasis has been placed on the control of the growth anisotropy which permits to preserve the initial orientation of the OP-GaAs substrate. Such a control has been demonstrated for pattern width and structure thickness ranging respectively from 1.8 to 300 μm and 20 to 500 μm. In the case of telecommunication applications such as wavelength conversion around 1.55 μm, where small periods are needed, a 20 μm thick regrown OP-GaAs layer is polished until epi-ready quality is reached for the further MBE (Molecular Beam Epitaxy) growth of guiding AlGaAs layers. Due to the remarkable weak surface corrugation (50 $\AA$) at the AlGaAs/GaAs interfaces, weak propagation losses are foreseen. Corresponding characterizations will be presented and the actual potential of HVPE-based OP-GaAs finally discussed for parametric conversion applications.

2:15 PM Z2.3
Submicrometer scale growth morphology control for the making of photonic crystal structures. Evelyne Gil-Lafon[1], Agnes Trassoudaine[1], Dominique Castelluci[1], Rachida Saoudi[2], Olivier Parriaux[2], Alain Muravaud[2] and Claire Darraud[3]; [1]LASMEA UMR CNRS 6602, Blaise Pascal University, Aubiere Cedex, France; [2]LTSI UMR CNRS 5516, University of Saint-Etienne, Saint-Etienne, France; [3]IRCOM UMR CNRS 6615, University of Limoges, Limoges, France.

Photonic crystal structures are realized by electron-beam lithography and reactive ion etching techniques through transfer masks nay micromanipulation. Severe etching conditions and many steps of process could result in the deterioration of photonic patterns so that existing techniques have mostly been developed for generating morphologically controlled defectless crystals to the detriment of free design capabilities. We propose a new route for making III-V compound photonic structures, either for 1D or 2D light guiding by using crystal growth rather than etching. The feasibility of such a growth approach relies on the use of a growth process which is mainly governed by the intrinsic crystal growth anisotropy. Hydride Vapour Phase Epitaxy (HVPE) makes use of chloride molecules as group III growth precursors. Because of the reversibility of the reactions involving these chloride molecules, HVPE appears as a near-equilibrium growth process. Consequently, perfect selectivity can be obtained whatever the mask design both in geometry and orientation. On the other side, growth appears mainly controlled by crystal intrinsic surface kinetics. Various growth morphologies have been stabilised by controlling the hierarchy of the growth rates of the low index faces of III-V crystals. Emphasis will be placed here on micrometer and submicrometer scale control of dielectric periodic structures constituted of 1 micrometer wide GaAs beams, pyramids and pillars alternately stacked with air grown by selective HVPE on GaAs substrates. Potential of the selective HVPE technique will be discussed for the making of high quality photonic structures, including 3D guiding patterns by using confined lateral growth.

2:30 PM Z2.4
Beam Induced Lateral Epitaxy: A New Way To Lateral Growth In Molecular Beam Epitaxy. Shigeya Naritsuka[1,2], Koji Saitoh[1], Takashi Suzuki[1] and Takahiro Maruyama[1,2]; [1]Materials Science and Engineering, Meijo University, Nagoya, Aichi, Japan; [2]21st century COE program "NANO FACTORY", Meijo University, Nagoya, Aichi, Japan.

Epitaxial lateral overgrowth is important for the fabrication of superior electronic and optoelectronic devices because the dislocation density in the overgrown layer is drastically reduced. We recently proposed an utterly new technique, named as beam induced lateral epitaxy (BILE), to achieve lateral overgrowth in MBE [1]. In BILE, lateral overgrowth is realized by incidence of molecular beam at a low angle to a substrate with a ridge structure. Then, selective growth can be achieved under a relatively low growth temperature without SiO_2 mask. Until now, BILE on GaAs (001) showed rather rough upper surface, which sometimes contained bumps [1]. In order to obtain a flat and smooth surface, we investigate the growth mechanism of BILE on GaAs (001) and GaAs (111)B substrates. The incident angle of the molecular beam and the crystal orientation of the ridge largely affected the grown shape of BILE layers through the formation of facets on the surface. In addition, shadow effect was also important to control the grown shape. For examples, the shadow of the neighboring ridge determined the under shape of the BILE layer because growth was suppressed in the shadow by the absence of the molecular beam. When the lateral growth front bumped upward, it also intercepted the molecular beam to a part of the upper surface and produced a large-size step on the surface. The use of (111)B substrate brought a flat and wide lateral growth on BILE by the formation of (111)B facet on the top surface. Reference: [1] T. Suzuki et al. Cryst. Res. Technol. 38, No. 7-8, 614-618 (2003).

2:45 PM Z2.5
Study of Anion Exchange Reaction at GaAs surfaces for heterojunction interface control. Maria Losurdo[1], April Susan Brown[2], Terence Brown[3], Greg Triplett[3], Gary May[3], Danilo Giuva[1] and Giovanni Bruno[1]; [1]PlasmaChemistry Center, IMIP-CNR, Bari, Italy; [2]Duke University, Durham, NC, North Carolina; [3]Georgia

Institute of Technology, Atlanta, GA, Georgia.

In recent years, great attention has been addressed to III-V semiconductor quantum heterostructures containing arsenides, phosphides, and antimonides for device applications, such as infrared photodetectors, lasers, and HBTs. These material systems offer flexibility in device design due to the wide range of available band alignments and band gaps. An understanding of III-V anion exchange reactions at heterojunction interfaces is of fundamental interest. The performance of these devices is strongly influenced by the composition, microstructure, and thickness of the heterointerfaces. Abrupt and atomically smooth interfaces require the control of the anion exchange and of the electronic and optical properties of the interface at atomic level resolution. Furthermore, very few non-destructive techniques allow quantitative measurement of the As, Sb or P anion interface segregation. Spectroscopic ellipsometry (SE) is a monolayer-sensitive interface technique that can be applied to the non-destructive compositional/microstructural analysis of superlattice (SLs). In this contribution, GaPyAs1-y/GaAs, GaAsySb1-y/GaSb and GaSbyAs1-y/GaAs superlattices (SLs) grown by MBE, respectively, by exposure of GaAs to a phosphorus and antimonide flux and by exposure of GaSb to an arsenic flux have been investigated by SE, covering the 0.75-5.5 eV photon energies. The SLs allow the study of the individual heterointerface formation. The SLs pseudodielectric function analysis gives information on the quality and composition of interfaces in the SLs and layer thickness Angstrom resolution. Complementary information on the composition of layers and abruptness of interfaces are obtained by XPS and XRD. We present studies on the abruptness of interfaces in these SLs as a function of surface temperature, of Sb or As soak time, of As precursor (As2 or As4), and of GaAs surface recontruction on the anion exchange. The GaAs surface reconstruction has strong impact on teh extent (in terms of both P(Sb)-surface coverage and in-diffusion). In particular, it is found that the As-rich reconstruction (2x4) reduces the P-surface coverage and hinders the P in-diffusion. Furthermore, we found that anion exchange results in the formation not only of a ternary alloy, but also in the formation of isoelectronic compounds AsSbx and asP that segregate at the GaSbAs/GaAs interface and GaAs surface, respectively. The As-for-Sb anion exchange reactions competes with the AsSb formation. A chemical-kinetic model that takes into account the competitive formation of isoelectronic AsSb and AsP compounds (neglected in the conventional thermodinamic and kinetic models) is proposed to explain the mechanism controlling the anion exchange reactions in GaPyAs1-y/GaAs, GaAsySb1-y/GaSb and GaSbyAs1-y/GaAs systems. The authors gratefully acknowledge the support of the Air Force Research Laboratory (F3361598C5428).

3:30 PM *Z2.6
Defect Engineering and Atomic Relocation Processes in Impurity-Free Disordered GaAs For Optoelectronic Devices Applications. Prakash Deenapanray, Department of Electronic Materials Engineering, Australian National University, Canberra, Australian Capital Territory, Australia.

Impurity-free disordering (IFD) has been actively researched for the past two decades regarding its potential application in optoelectronic devices integration. The technique makes use of a silica capping layer on the semiconductor structure, which acts as a pump for Ga atoms during a high temperature annealing step. The resulting injection of an excess of Ga vacancies, VGa, below the semiconductor surface then promotes disordering, and hence a change in the band gap of the semiconductor heterostructure. Although the technique is relatively simple and has been successfully applied for the fabrication of devices, there are several materials issues which are yet to be resolved before IFD can be translated into a full-fledged integration technique for III-V semiconductor devices. In particular, the operative mechanisms underlying the IFD process, namely its defect engineering aspects and the segregation of impurities are not well understood. In this paper, we will discuss the types of defects created in both n- and p-type GaAs by IFD. We demonstrate the influence of stress on the defect generation rates in the n-type GaAs epitaxial layers. Furthermore, we demonstrate that the concentration of defects in GaAs and AlxGa1-xAs ($0 < x < 0.3$) can be controlled by using doped spin-on-glass layers. Furthermore, we demonstrate that results which are applicable to undoped structures cannot naively be translated to doped materials because of dopant redistribution, especially Zn, during the IFD process. Some ways to mitigate this detrimental dopant redistribution is proposed for applications in device fabrication.

4:00 PM Z2.7
Energy-Filtered Scanning Tunneling Microscopy Using III-V Semiconductor Probe Tips. Peter Sutter[1], Eli Sutter[1], Percy Zahl[1,2], James Bernard[1] and Ian Carl Schick[1]; [1]Physics, Colorado School of Mines, Golden, Colorado; [2]IBM Zurich Research Labs, Rueschlikon, Switzerland.

The electronic and optoelectronic properties of III-V semiconductors and heterostructures make these materials attractive for a wide variety of applications. Well-known examples are semiconductor lasers, microelectronic devices, and solar cells. We have explored the potential of III-V materials for use as probe tips in scanning tunneling microscopy (STM). Performing STM with cleaved InAs tips, we are able to demonstrate routine atomic resolution in imaging of semiconductor surfaces, such as Si(111)-(7x7). More importantly, we find that the band structure of an InAs tip gives rise to efficient energy-filtering of the tunneling current in STM [1]. Only sample states that align with extended states in the projected bulk band structure of the tip can contribute to the tunneling current, while sample states that align with a fundamental or projected gap give no contribution. The acceptance window of these tips is easily adjustable via tuning of the bias voltage between tip and sample, a capability that we use to select a specific sample state for imaging. Replacing the conventional metal STM tips by a III-V semiconductor thus provides a powerful new pathway to atomic level spectroscopic imaging, with possible applications ranging from measuring the local surface composition of a random alloy 'atom-by-atom' to creating bond-specific maps of single molecules. While our first experiments were performed with bulk InAs tips, other III-V semiconductors will have similar energy-filtering capability if gaps exist in their projected bulk band structure. The energy-filtering characteristics could thus be altered by choosing a different tip material. Ultimately, the band structure of semiconductor STM probes may be tailored to tune and optimize spectroscopic contrast, drawing from the broad repertoire of tools developed for band-structure engineering, including alloying, carrier confinement, and elastic strain. [1] P. Sutter, P. Zahl, E. Sutter, and J.E. Bernard, Phys. Rev. Lett. 90, 166101 (2003).

4:15 PM Z2.8
Growth and Characterization of InAs Epitaxial Layer on GaAs (111) B. Hong Wen, Zhiming Wang and Greg Salamo; University of Arkansas, Fayetteville, Arkansas.

The strain driven self-assembly of InAs nano-structures in a GaAs matrix is of great interest for compound semiconductor research and applications. The knowledge of InAs growth behavior along four low index GaAs substrate orientations, (100), (110), (111)A and (111)B, is a prerequisite to control the formation of InAs nanostructures in the GaAs matrix. It is well known that InAs growth on GaAs (100) leads to three-dimensional islands through the S-K mode at normal growth conditions. The InAs epitaxial growth is observed to remain a two-dimensional growth mode on GaAs (110) and GaAs (111)A. However, the InAs growth behavior on GaAs (111) B is still controversially discussed. We report here a Scanning Tunneling Microscopy (STM) study of InAs growth on GaAs (111) B, by Molecular Beam Epitaxy (MBE), as a function of the InAs thickness to clarify this issue. Misoriented N+-GaAs (111)B substrates with 2 degree towards [2-1-1] were used in this work. It was found that the misorientation is very helpful to obtain a smooth GaAs buffer surface as a starting template for InAs overgrowth. Although 2 mono-layer (ML) InAs growth leads to 3D islands on GaAs (100), it maintains an ideal 2D growth mode on GaAs (111)B. The resulting surface for 2ML InAs growth was observed to be characterized by ragged monolayer steps. Further InAs deposition (3 monolayer and 4 monolayer InAs growth) results in step bunching. The built-in strain is observed to be released through the formation of dislocation at around a thickness of 6 ML, as demonstrated by disappearance of the photoluminescence from the InAs layerThe bunched giant steps still exist up to a deposition of 10 ML. At no time, during the entire study, was strain-driven 3D islands observed. In this talk we will also report on the reconstruction observed for the InAs epitaxial layer on GaAs(111)B.

4:30 PM Z2.9
Pulsed Laser Deposition of Bi- and Sb-based Solid Solutions and Multilayer Structures. Arik G. Alexanian[1], Garegin A. Aleksanyan[1], Nikolay S Aramyan[1], Hovsep N Avetisyan[2], Karapet E Avjyan[1], Romen P. Grigoryan[3], Ashot M. Khachatryan[1] and Arsham S. Yeremyan[1]; [1]Dept. of Semiconductor Electronics, Institute of Radiophysics & Electronics, Ashtarak, Armenia; [2]Istitute for Physical Research, Ashtarak-2, Armenia; [3]Yerevan Physics Institute, Yerevan, Armenia.

Thin films of Bi, Sb, solid solutions Bi1-xSbx, as well as multilayer structures Bi-Sb-Bi-Sb– from elementary sources were produced by pulsed laser deposition for optoelectronic applications. KBr-type crystals were used as substrates. The solid solutions Bi1-xSbx were obtained by co-evaporation from single targets of Bi and Sb. Structural investigations show that the performance of produced films depends on both the amount of material deposited per pulse of laser energy and the ratio of this amount for bismuth and antimony. Based on this the technological regimes of growth temperature and laser fluence ranges were determined in which single-crystalline growth of films with certain x is possible. Single-crystalline films of Bi1-xSbx

were obtained in the range of x values from 0.12 to 0.48, which corresponds to semiconductor state of this solution. The method of sequential deposition is used for fabrication of multilayer structures Bi/Sb with quantum-confined layers of bismuth. The growth regime with practically excluded interdiffusion of materials is found. Spectral analyses confirm the predicted semimetal-to-semiconductor transition of bismuth as a result of quantum confinement, which results in possibilities to use the originated properties for light-emitting and detecting devices.

4:45 PM Z2.10
Growth of Icosahedral $B_{12}P_2$ Thin Films on 6H−SiC(0001) By Chemical Vapor Deposition. Peng Lu[1], James H Edgar[1] and Terrence L Aselage[2]; [1]Chemical Engineering, Kansas State University, Manhattan, Kansas; [2]2525/MS0613, Sandia National Laboratories, Albuquerque, New Mexico.

The parameters necessary to deposit high quality icosahedral boron phosphide ($B_{12}P_2$) thin films on on and off−axis Si−face 6H−SiC(0001) substrates by chemical vapor deposition are reported. Icosahedral boron phosphide ($B_{12}P_2$) is a refractory wide band gap (Eg=3.3eV) semiconductor potentially suitable for the fabrication of beta−cells, devices for direct nuclear−to−electrical energy conversion. Ultra high purity BBr_3 and PBr_3 were used as reactants, with hydrogen as the carrier gas. The c−axis of the $B_{12}P_2$ films was aligned with the c−axis of the substrate at temperatures above 1350C°. The surface morphologies change from very fine crystalline grains at 1350C° to smooth, mirror−like surface at 1700C°. The optimum BBr_3 to PBr_3 flow rate ratio is 1 to 1 with respect to surface morphology and moderate growth rate of 8μm/hr. Higher growth rates were obtained by increasing the BBr_3 flow rate, but the surfaces became very rough. The crystalline properties of the films were characterized by XRD and Raman spectroscopy, and the surface morphologies investigated by SEM and AFM.

SESSION Z3: Emitters, Detectors, and Solar Cells
Chairs: John Benner and Gail J. Brown
Tuesday Morning, December 2, 2003
Room 208 (Hynes)

8:30 AM *Z3.1
Impact Ionization in Narrow Bandgap Superlattice Avalanche Photodiodes. Christoph Grein[1], Henry Ehrenreich[2] and Michael Flatte[3]; [1]Physics M/C273, U. Illinois at Chicago, Chicago, Illinois; [2]Physics, Harvard University, Cambridge, Massachusetts; [3]Physics and Astronomy, U. Iowa, Iowa City, Iowa.

A theoretical analysis directed towards engineering the electronic band structures of narrow bandgap superlattices that control the ratio of the hole- to electron-impact ionization coefficients is presented. The electronic band structures are computed employing a 14-band superlattice K.p formalism generalized to an arbitrary number of layers in a superlattice unit cell. Impact ionization rates are calculated from the K.p bands by direct integration over possible initial and final states. Finally, impact ionization coefficients are then evaluated using high field Monte Carlo transport calculations to obtain carrier distribution functions and drift velocities. Quantitative results are presented for short-infrared (2.3 micron cutoff wavelength) to long-infrared (12.2 micron) 3- and 4-layer superlattices having AlAs, InGaAs, InGaSb and/or AlSb layers. The superlattice designs are sufficiently flexible to permit the placement of valence bands at locations that promote hole-initiated impact ionization without a corresponding increase of electron-initiated impact ionization. Alternatively, conduction bands can be located in such a way as to promote electron-initiated impact ionization without increasing the hole-initiated impact ionization. As a result, appropriately designed superlattices will have ratios of hole- to electron-impact ionization coefficients much different from one. Such ratios are predicted to yield avalanche photodiodes with low excess noise factors and large gain-bandwidth products when the superlattices are used in the multiplication regions.

9:00 AM Z3.2
Internal efficiency of high-brightness AlGaInP LEDs. Paola Altieri, Arndt Jaeger, Reiner Windisch, Norbert Linder, Raimund Oberschmid and Klaus Streubel; Osram OS Regensburg Germany, Regensburg, Germany.

We report a quantitative analysis of the internal quantum efficiency of high-brightness $(Al_xGa_{1-x})_{0.5}In_{0.5}P$ light-emitting devices (LEDs), with an emission wavelength ranging from 644 nm to 560 nm. The wavelength is adjusted varying the Aluminium content in the active LED layer. We are able to evaluate separately the losses due to nonradiative recombination in the active layer and the losses due to carrier leakage, as a function of the emission wavelength. The evaluation is based on measurements of the external quantum efficiency of the LEDs as a function of the operating current and the junction temperature. The current and temperature dependencies are compared to an analytical model in order to obtain quantitative information on the internal efficiency and losses. The model is based on a rate equation that takes into account the radiative and non-radiative recombination as well as diffusive leakage of charge carriers into the confining layers. Using a ray-tracing simulation, also photon recycling and its influence on the light extraction efficiency is included in the calculation. The analysis provides the wavelength dependence of both the nonradiative recombination as well as the carrier leakage. In the emission wavelength range 602-644nm, the LEDs show maximum internal quantum efficiencies above 90%. The maximum efficiency decreases with decreasing wavelength, down to about 7% for the LEDs emitting at 560 nm. This reduction is manly due to leakage, which accounts for the loss of about 75% of the injected carriers. In addition, the non-radiative recombination increases with increasing Aluminium content, changing by approximately one order of magnitude between red and green LEDs. This result is discussed in terms of Γ-X scattering as well as impurities in the active layer.

9:15 AM Z3.3
Impurity dominant layer disordering of AlGaInP/GaInP multi-quantum well laser diodes. Yong Bum Kwon[1], In Woo Kim[1], Jae Mok Yi[1], Jung Ho Je[1], Chong Cook Kim[2], Pierre Ruterana[3] and Gerard Nouet[3]; [1]POSTECH, Pohang, South Korea; [2]Samsung Electro-Mechanics Co., Suwon, South Korea; [3]CNRS/ISMRA, CAEN, France.

AlGaInP/GaInP multi-quantum well (MQW) systems with wide direct band gaps have been used for LDs and LEDs in the red to green light regions. Intermixing between the layers in the MQW superstructure is one of the important issues in LD devices. Various factors such as impurity induced layer disordering (IILD), vacancy enhanced disordering (VED) or thermal disordering (TD) are known to induce the intermixing of layers during the post-growing process of current blocking layer. In this study we investigated the layer disordering by comparatively studying the Zn doped and un-doped AlGaInP/GaInP MQW samples using synchrotron X-ray scattering and secondary ion mass spectroscopy (SIMS). From the GaAs[11l] scattering profiles, we observed no intermixing in as-grown samples. However, at an annealing temperature of 640°C, the intermixing occurred for Zn doped MQW, but not for un-doped MQW. These results suggest that the layer disordering is caused by IILD, not by VED or TD. SIMS results also support the disordering by IILD.

9:30 AM Z3.4
Growth and Properties of AlGaInP Resonant Cavity Light Emitting Diodes (RCLEDs) on Ge/SiGe/Si Substrates. Ojin Kwon[1], John J. Boeckl[1], Minjoo L. Lee[2], Arthur J. Pitera[2], Eugene A. Fitzgerald[2] and Steven A. Ringel[1]; [1]Electrical Engineering, The Ohio State University, Columbus, Ohio; [2]Materials Science and Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts.

Integrating light emitting devices with conventional high-density Si electronic devices is of great interest to form high-speed optoelectronic integrated circuits (OEICs) for a variety of interconnect and network applications. In this paper successful monolithic integration of high performance AlGaInP based light emitting diodes on Ge/SiGe/Si substrates by using solid molecular beam epitaxy is presented. AlGaInP based resonant cavity LED (RCLED) were grown and processed on relaxed, low dislocation density Ge/SiGe/Si substrates, as well as Ge and GaAs substrates for comparison purposes. Triple axis x-ray diffraction and photoluminescence measurements were used to optimize growth conditions. The one-λ cavity of RCLED consisted of four $Ga_{.51}In_{.49}P$ quantum wells with $(Al_{.5}Ga_{.5})_{.51}In_{.49}P$ barriers and $AlAs/Al_{.5}Ga_{.5}As$ was used as distributed Bragg reflectors (DBRs) such that the reflectivities of top and bottom mirror were designed to attain ∼74% and ∼97%, respectively. This design was chosen to minimize parasitic absorption in the lower bandgap Ge and Ge/SiGe/Si substrates, thereby maximizing extraction efficiency. Cross sectional transmission electron microscopy confirmed that high-quality, ideal low-mismatched GaAs/Ge interfaces with efficient, short range (<10nm) annihilation of anti-phase domains, as well as extremely abrupt interfaces through entire device structure including the quantum wells and the DBR layers, were achieved on the Ge/SiGe/Si substrates. For devices on Si, the maximum optical power measured was 66μW with 663nm peak wavelength under 300mA injection current and narrow FWHM value of 7nm under 160mA injection current was obtained. Furthermore, minimal peak wavelength shift of $\Delta\lambda/\Delta I \sim 0.18$Å/mA was measured under injection current ranging from 40mA to 400mA from 350μm×350μm device. For comparison, the maximum optical power obtained for devices on Ge and GaAs substrates were 42.2μW and 41.2μW, respectively. Correlations between material and device properties will

be presented, along with a discussion on the use of supplementary $Al_{.67}Ga_{.33}As$ current spreading layers for the RCLED on Si.

9:45 AM Z3.5
Non-Contact Determination of Free Carrier Concentration in n-GaInAsSb. James Edgar Maslar[1], C A Wang[2], W S Hurst[1] and D A Shiau[2]; [1]NIST, Gaithersburg, Maryland; [2]Lincoln Laboratory, Massachusetts Institute of Technology, Lexington, Massachusetts.

GaSb-based semiconductors are of interest for mid-infrared optoelectronic and high-speed electronic devices. Accurate determination of electrical properties is essential for optimizing the performance of these devices. However, electrical characterization of these semiconductors is not straightforward since semi-insulating (SI) GaSb substrates for Hall measurements are not available. In this work, the capability of Raman spectroscopy for determination of the majority carrier concentration in n-GaInAsSb epilayers was investigated. Raman spectroscopy offers the advantage of being non-contact and spatially resolved. Furthermore, the type of substrate used for the epilayer does not affect the measurement. However, for antimonide-based materials, traditionally employed Raman laser sources and detectors are not optimized for the analysis wavelength range dictated by the narrow band gap of these materials. Therefore, a near-infrared Raman spectroscopic system, optimized for antimonide-based materials, was developed. Ga0.85In0.15As0.13Sb0.87 epilayers were grown by organometallic vapor phase epitaxy with doping levels in the range 2 to 80 x 1017 cm-3, as measured by secondary ion mass spectrometry. For a particular nominal doping level, epilayers were grown both lattice matched to n-GaSb substrates and lattice-mismatched to SI GaAs substrates under nominally identical conditions. Single magnetic field Hall measurements were performed on the epilayers grown on SI GaAs substrates, while Raman spectroscopy was used to measure the carrier concentration of epilayers grown on GaSb and the corresponding SI GaAs substrates. Compared to Hall measurements, Raman spectra indicated that the GaInAsSb epilayers grown on GaSb substrates have higher free carrier concentrations than the corresponding epilayers grown on SI GaAs substrates under nominally identical conditions. This is contrary to the assumption that for nominally identical growth conditions, the resulting carrier concentration is independent of substrate, and possible mechanisms will be discussed.

10:30 AM *Z3.6
Performance of LWIR InAs/GaSb SLS PIN Photodiodes. Gerry J Sullivan[1], Roger De Wames[1], Josh Bergman[1], Jim Waldrop[1], Christoph Grein[2] and Michael Flatte[3]; [1]Advanced Devices, Rockwell Scientific, Thousand Oaks, California; [2]Dept. of Physics, Univ. of Illinois at Chicago, Chicago, Illinois; [3]Dept. of Physics, Univ. of Iowa, Iowa City, Iowa.

LWIR InAs/GaSb short period superlattices (SLSs) PIN photodiodes have been fabricated and characterized. The structures were grown (growth 133) on (100) oriented GaSb substrates by elemental source MBE. The repeated pattern in the SLS was intended to contain 16 monolayers of InAs, 0.5 monolayer of InSb (InSb-like interface), 7 monolayers of GaSb, and 0.5 monolayer of InSb. This pattern was repeated 448 times, with p-type doping (Be) added to the first 0.5 um of SLS, no intentional doping for 2 um, and n-type doping (Si) added to the final 0.5 um. The SLS period, as measured by X-ray, is 66.30 Angstroms, and the SLS is in compression by 0.19%. The wafers were etched to form mesas, metalized to form diodes, and mounted into packages. There are no intentional AR coatings. The cut-off wavelength of the diodes at 40K is 10.5 microns. The external quantum efficiency, uncorrected for reflection from the device and measured at 9.02, microns, is 25%. This is a very encouraging QE, for an SLS structure that is only three microns thick. The measured QE increases with decreasing wavelength, with good agreement between the shape of the theoretically predicted and measured QE. The dark currents in the devices are dominated by side-wall leakage, even in the largest diameter (400 um) diodes. Details of the characteristics, and the performance of "passivation" layers on the mesa's sidewalls will be discussed. Our results will be compared with other published results. This work is sponsored by Air Force and Missile Defense Agency, and the Contract Technical Officer is Dr. Gail Brown, of AFRL/MLPS.

11:00 AM Z3.7
Multilayer Bi/Sb Structures for Generation of IR Radiation. Arik G. Alexanian, Garegin A. Aleksanyan and Arsham S. Yeremyan; Dept. of Semiconductor Electronics, Institute of Radiophysics & Electronics, Ashtarak, Armenia.

Multilayer structures with dimensionally quantized layers of bismuth and the possibilities of their use for reception and generation of IR radiation are investigated. Quantum localization of carriers in the potential well initiates the transition of bismuth from initial semimetal to semiconductor state. In the case when the quantization direction is parallel with trigonal axis, the originated new electron energy structure is characterized by an indirect energy gap. We show that as a result of quantum confinement the indirect non-radiative transitions transform to radiative (photon-assisted) transitions at certain thicknesses of size-quantized layers, which can be used for generation and reception of far IR radiation. For multilayer structures Bi-Sb-Bi-Sb– (with quantum wells in bismuth) the electron structure and the probability of photon-assisted transitions are calculated taking into account the interaction of neighboring quantum wells. It should be noted that choosing other quantization direction (relative to trigonal axis), which is possible with current technological methods semiconductor state can be realized with direct energy gap.

11:15 AM Z3.8
Submillimeter Radiation - Induced Persistent Photoconductivity in $Pb_{1-x}Sn_xTe$(In). Aleksander Kozhanov[1], Dmitriy Dolzhenko[1], Ivan Ivanchik[1], Dan Watson[2] and Dmitriy Khokhlov[1]; [1]Physics Department, Moscow State University, Moscow, Russian Federation; [2]Department of Physics and Astronomy, University of Rochester, Rochester, New York.

Doping of the lead telluride and related alloys with some of the group III impurities (In, Ga) results in appearance of unusual effects such as the Fermi level pinning and the persistent photoconductivity at low temperatures. The spectra of the persistent photoresponse have not been measured so far because of the difficulties with screening the background radiation. We report on the observation of strong persistent photoconductivity in $Pb_{0.75}Sn_{0.25}Te$(In) under the action of monochromatic submillimeter radiation at wavelengths of 176 and 241 microns. The sample temperature was 4.2 K, the background radiation was completely screened out. The sample was initially in the semiinsulating state providing dark resistance of more than 100 GOhm. The responsivity of the photodetector is by several orders of magnitude higher than in the state of the art Ge(Ga). The red cut-off wavelength exceeds the upper limit of 220 microns observed so far for the quantum photodetectors in the uniaxially stressed Ge(Ga). It is possible that the photoconductivity spectrum of $Pb_{1-x}Sn_xTe$(In)covers all the submillimeter wavelength range.

11:30 AM Z3.9
Compound Semiconductors as the Materials of Multiband Photovoltaic Cells. Lianghuan Feng, Yaping Cai, Jingquan Zhang, Lili Wu, Wei Li, Wei Cai, Jiagui Zheng, Bing Li, Zhi Lei and Qiang Yan; Department of Materials Science, Institute of Solar Energy Materials and Devices,Sichuan University, Chengdu, Sichuan Province, China.

Recently, A.Luque et al and M.Green have proposed and discussed the concept of multi-band photovoltaic cells (MBPVC). They have shown efficiency advantages if a third band is included into the inversion process, and mentioned two paths to establish the third band: impurity band and multiple quantum wells. In the paper, we have studied the applications of some compound semiconductors for MBPVC, considering the direct band gap with different wideness of the semiconductors. For the impurity band MBPVC, the minimal optical losses of some elected compound semiconductors of wide band gap, such as ZnTe, CdS, ZnSe, CdO, TiO_2, ZnO and In_2O_3, are calculated in the conditions of AM0 and AM1 when the impurity band is at an appropriate deepness inside the band gap. The optical loss decreases with an increase of gap wideness, for example, it is 32.8% for CdS and 21.6% for In_2O_3, which are much lower than 52% for standard crystal Si solar cells. The heat balance process of electrons transition through the impurity band and carriers transportation in the third band have been investigated, and the minimal state density in impurity band and concentrations of doping atoms have been estimated. In experiments, un-doped and doped ZnTe and ZnSe polycrystalline films have been deposited by co-evaporation. For multiples quantum well MBPVC, CdTe/ZnTe, ZnSe/CdSe and ZnS/CdS multiple quantum wells are interesting due to their small valence band or conductance band offsets which are 0.05 eV, 0.11 eV or 0.0 eV, respectively, as well as the appropriate quantum well deepness of 0.77 eV, 0.86 eV and 1.28 eV, respectively. The excitation process of electrons and transportation mechanism of carriers in the multiple quantum wells have been analyzed. From the physics of MBPVC, the results have been discussed.

11:45 AM Z3.10
A New Class of Solar Cells: Isomeric Boron Carbide Semiconductors with Fourth Quadrant Conductivity. Ravi B. Billa[2], A. N. Caruso[3] and Jennifer I. Brand[1]; [1]College of Engineering and Center for Materials Research and Analysis, Univ. of Nebraska, Lincoln, Nebraska; [2]Department of Mechanical Engineering, Univ. of Nebraska, Lincoln, Nebraska; [3]Department of Physics, Univ. of Nebraska, Lincoln, Nebraska.

Previously, we have made diodes[1,2] and transistors [3] as well as very effective real-time solid state neutron detectors [4] out of semiconducting boron carbide deposited on silicon or silicon carbide.

In this work the recent fabrication of a new class of highly photosensitive boron carbide diodes is discussed. These diodes exploit the electronic behavior differences of the isomers of film precursors, the closo-dicarbododecaboranes. These differences were observed in photoemission and inverse photoemission studies where the HOMO-LUMO (highest occupied molecular orbital-lowest unoccupied molecular orbital) gap variations upon deposition varied strongly with the isomeric configuration. Based on these results, p-n junctions were formed by plasma enhanced chemical vapor of ortho and meta carborane, respectively, on both nickel and aluminum substrates. These diodes exhibit fourth-quadrant conductivity, making them exciting new photovoltaic conversion devices. 1. Lee, SW; Dowben, PA; Applied Physics A 58 (3): 223-227 (1994) 2. Byun, DG; Hwang, SD; Dowben, PA; Perkins, FK; Filips,F; Ianno, NJ. Applied Physics Letters 64(15): 1968-1970(1994) 3. Hwang, SD; Byun, D; Ianno, NJ; Dowben, PA; Kim, HR. Applied Physics Letters 68(11): 1495-1497(1996) 4. Robertson, BW; Adenwalla, S; Harken A; Welsch, P; Brand, JI; Dowben, PA; Claasen, JP Applied Physics Letters 80(19): 3644-3646 (2002)

SESSION Z4: Devices
Chairs: Anneli Munkholm and Christine Wang
Tuesday Afternoon, December 2, 2003
Room 208 (Hynes)

1:30 PM *Z4.1
An InAs Based Transistor Approach to Terahertz Electronics: Concepts and Materials Science. Jerry M. Woodall, Yale University, New Haven, Connecticut.

Owing to its small band gap, high electron mobility, and high saturation drift velocity, InAs is an appealing candidate for low power and ultra-high speed (THz) device applications. However, InAs has not been well studied in the past for such applications because of the lack of a suitable lattice-matched substrate or latticed-matched heterostructure to facilitate the design and fabrication of desirable transistors. This talk will present our device concepts and materials science of our new enabler: InAs and related alloys grown on GaP substrates. A key feature of InAs grown on GaP is the self annihilation of threading dislocations generated by the 11% lattice mismatch between InAs and GaP. This annihilation results in differential electron mobilities of 20,000 cm^2/volt-sec for only 2 microns of epilayer growth, a surprising and happy result in our quest of THz devices.

2:00 PM Z4.2
Shallow Ohmic Contacts to p-InAs and p-InGaSb for HBT's. Eric Lysczek[1], Sammy Wang[1], Joshua Robinson[1], Brian Bennett[2] and Suzanne Mohney[1]; [1]Materials Science and Engineering, The Pennsylvania State University, University Park, Pennsylvania; [2]Naval Research Laboratory, Washington, District of Columbia.

There has been great interest recently in heterojunction bipolar transistors fabricated from compound semiconductors with lattice parameters near 6.1 or 6.2$\AA$. The ohmic contact to the base of these devices must not only exhibit a low resistance, it must also be very shallow, since the base may be less than 50 nm thick. Both Ti/Pt and Ti/Pt/Au ohmic contacts to p-InAs have been reported in the literature. In our study, a Pd/W/Au contact we recently developed for p-InGaSb is tested on p-InAs and compared to the conventional Ti/Pt/Au contact. In the as deposited condition, an average specific contact resistance of 2.6 x 10^{-6} Ω cm^2 was measured for 14 sets of Ti/Pt/Au contacts, while the specific contact resistance for the Pd/W/Au (5/50/145 nm) contacts was reproducibly lower, with an average value of 2.0 x 10^{-6} Ω cm^2 for 16 sets of contacts. Only mild annealing conditions may be considered for the devices. The specific contact resistance for the Ti/Pt/Au contact was reduced to 2.3 x 10^{-6} Ω cm^2 after 30 s at 175°C in UHP Ar, but the specific contact resistance of the Pd/W/Au contacts dropped to 1.1 x 10^{-6} Ω cm^2 after the same annealing schedule. We know from our previous work that the Pd/W/Au contact is shallow and thermally stable on p-$In_{0.25}Ga_{0.75}Sb$. Palladium is employed for making intimate contact to the p-InGaSb, the W barrier protects the semiconductor from reaction with Au, and Au lowers the metal sheet resistance. Recent experiments to make the contact to InGaSb shallower through the use of new semiconductor surface preparations and a thinner Pd layer have been conducted, and TEM has been performed to supplement previous Auger depth profiles. Materials characterization will also be performed on the Pd/W/Au contacts to p-InAs. We acknowledge HRL for InAs epilayers.

2:15 PM Z4.3
MOCVD Growth of InAlAsSb Layer for High-Breakdown Voltage HEMT Applications. Haruki Yokoyama[1], Hiroki Sugiyama[1], Yasuhiro Oda[1], Michio Sato[1], Takashi Kobayashi[1] and Noriyuki Watanabe[2]; [1]NTT Photonics Laboratories, Atsugi, Japan; [2]NTT Advanced Technology Corporation, Atsugi, Japan.

Interest in the application of InAlAsSb quaternary alloys, which have a high Schottky barrier and high-energy band gap, is increasing for use in high-breakdown voltage devices and mid-infrared optoelectronic devices. However, few reports describe the metalorganic chemical vapor deposition (MOCVD) growth of InAlAsSb, in particular important information for composition control. This report is the first to describe the decomposition feature of source gases during InAlAsSb growth. Moreover, it shows the significantly improved characteristics of a high electron mobility transistor (HEMT) with InP/InAlAsSb Schottky layer. Growth was carried out using a horizontal-type low-pressure (77 Torr) MOCVD reactor. The epitaxial layers were grown on semi-insulating InP substrates. The group-III sources were triethylgallium (TEG), trimethylaluminum (TMA), and trimethylindium (TMI). Arsine, phosphine, and trimethylantimony (TMSb) were used as the group-V sources. The solid composition of InAlAsSb layer was determined by inductively coupled plasma atomic emission spectroscopy (ICP-AES). From the composition analysis of InAlAsSb layers grown at various TMSb flow rates, it was found that the Al composition in InAlAsSb, as well as the growth rate of InAlAsSb, decreased as TMSb flow rate increased. To clarify the reason for this, the growth rates of InAsSb and AlAsSb components were estimated. The growth rate of AlAsSb component mirrored the InAlAsSb growth rate, but that of InAsSb was almost constant. This means that the decomposition of TMA is suppressed by TMSb supply. It is deduced that the excess Sb on the growth surface is related to this suppression. In order to demonstrate the effectiveness of a high Schottky barrier, a HEMT with InP/InAlAsSb Schottky layer was grown. The I-V characteristics of the fabricated Schottky diode confirm that the reverse current of InP/InAlAsSb is about one order of magnitude smaller than that of commonly used InP/InAlAs.

2:30 PM Z4.4
Evidence for localization effects in GaAsSb/InP heterostructures from optical spectroscopy. Chouaib Houssam[1], C. Bru-Chevallier[1], T. Benyattou[1], H. Lahreche[2] and P. Bove[2]; [1]Laboratoire de Physique de la Matiere, UMRCNRS 5511, INSA de Lyon, Lyon, France; [2], Picogiga, Paris, France.

This work lies within the scope of a project which aims to realize a new Heterojunction Bipolar Transistors generation (HBT) on InP with a GaAsSb base, in order to elaborate high-speed digital circuits (80 to 100 Gbits/s). Emitter-base interfaces between GaAsSb and InP need to be well controlled to ensure good performance of the HBT, and this requires a careful analysis of both material and interface quality. Photoluminescence (PL) experiments as a function of temperature and of power excitation density, as well as photoreflectance (PR) measurements are performed on GaAsSb/InP heterostructures in order to get information about ordering and segregation effects in antimonide alloys. From the PL recombination energy across the type II interface and at the GaAsSb band-edge, the band offset ΔEc between InP and GaAsSb can be calculated. The evolution of the PL peak energy versus temperature is atypical in the sense that it starts to grow when the temperature increases before decreasing at higher temperature. This so-called inverted "S-Shape" is characteristic of localization effects, and has already been observed in AlInAs alloys on InP[1] and also more recently in slightly nitrided GaAsN alloys[2]. In this situation of significant localization effects, the evolution of the integrated PL intensity according to the temperature is well adjusted by an equation classically used for amorphous semiconductors. At low temperature, the shape of the PR spectra results in an atypical steplike background, which is linked to the carrier localization effects. The mechanism inducing the steplike lineshape of the PR spectrum is analyzed as a band filling effect in consequence of the carrier localization on potential fluctuations. 1.Driessen F.A.J.M., Bauhuis G.J., Olsthoorn, S.M., Giling, L.J.(1993) Phys.Rev.B,Vol 48 n 11,pp.7889-7896. 2.Grenouillet, L. Bru-Chevallier, C., Guillot, G., Gilet, P., Duvaut, P., Vannuffel, A., Million, A., Chenevas-Paule, A. (2000)Appl.Phys.Lett., vol 76,pp2241-2243.

2:45 PM Z4.5
Modeling of Recombination Lifetimes in Charge-separation Device Structures. Jamiyanaa Dashdorj[1,2], Richard Ahrenkiel[1] and Wyatt Metzger[1]; [1]Measurement & Characterization Division, NREL, Golden, Colorado; [2]Physics Department, Colorado School of Mines, Golden, Colorado.

It is well known that the recombination processes in semiconductors are inhibited by charge-separation mechanisms that are produced by structures such as p-n junctions. In this work, we calculated the recombination rates in several p-n junction structures by both analytical and numerical techniques. The various methods show that the transport effects can be divided into two separate events. The first is the primary flow of photocurrent that results in the build-up of a

junction voltage. The time constant of this effect is a function of the minority-carrier diffusion coefficient and the physical width of the absorbing medium. In most semiconductor structures, this time constant is relatively short relative to the recombination lifetime. For thin-film structures, this zero-field time-of-flight (ZTOF)[1] is of order d^2/D, where d is the film thickness and D is the ambipolar diffusion coefficient. The second effect is the discharge of the open-circuit voltage of the p-n junction by minority-carrier charge injection (in the dark). This current, called the "dark current" in photovoltaic devices, is designated by J_0. Analysis of the long-term decay in this regime indicates that the decay time varies as $KT/q\ C_J/J_0$, where C_J is the junction capacitance. In this regime, the decay time is a function of recombination lifetime through the dependence of J_0 on the latter. However, the excess-carrier decay time is not the true recombination lifetime. The measured decay time depends on the measurement technique employed. In time-resolved photoluminescence measurements, one sees the Δnp or Δpn product decay in time. In photoconductivity-based measurements, one sees $\Delta n\mu_n + \Delta p\mu_p$ decay. These two quantities may give different results in charge-separated systems. [1]R.K.Ahrenkiel et al. Appl. Phys. Lett. **49**, 725 (1986)

3:30 PM Z4.6
Observation of retarded recombination in charge separation structures. Richard Keith Ahrenkiel[1], Daniel Friedman[1], Wyatt Metgzer[1] and Jamiyana Dashdorj[1,2]; [1]National Center for Photovoltaics, National Renewable Energy Laboratory, Golden, Colorado; [2]Department of Physics, Colorado School of Mines, Golden, Colorado.

Measurements of recombination and minority-carrier lifetimes have become a standard activity in current semiconductor technology. The two primary measurement techniques are based on photoconductive decay (PCD) and time-resolved photoluminescence (TRPL). Measuring the "true" lifetime depends on the both carrier types being confined to a given spatial region of a diagnostic device. When internal electric fields exist, that separate the charges, the measured value does not represent the real minority-carrier lifetime. In these cases, the measured quantity depends on the measurement technique. In this work, we have observed charge-separation effects in a variety of structures and materials by both PCD- and TRPL-based techniques. In epitaxial GaAs structures, the recombination lifetime is observed in confinement structures and then compared in other structures such as p-n junctions and type II heterostructures. As an example, the theoretical radiative lifetime in epitaxial GaAs, doped to 1 x 1017 cm-3, is about 100 ns. However, in a similarly doped p-n junction, the PCD lifetime increased to 10 to 50 microseconds because of charge separation. In similarly doped p-GaAs/p-GaInP heterostructures, which exhibit type II behavior, the measured PCD lifetime was 1 to 2 milliseconds. The complementary TRPL measurements, on the same structures, produced lifetime values that were much shorter than the expected radiative lifetime. In these cases, we believe that the measured TRPL decay time represents the charge-separation transient, rather than a recombination lifetime. Similar results were found for silicon wafers that were measured in a surface-passivating solution. The growth of a p-n junction by diffusion produces significant increases in the PCD lifetime. These experimental results will be compared with the theory developed in a companion presentation. Taken together, we will show that specific device models must be used to analyze charge-separation structures in order to get useful parameters from the measurement.

3:45 PM Z4.7
Pump Wavelength Tuning of Optical Pumping Injection Cavity Lasers for Enhanced Mid-Infrared Operation. T C McAlpine[1], K R Greene[1], M R Santilli[1], Linda J Olafsen[1], W W Bewley[2], C L Felix[2], I Vurgaftman[2], J R Meyer[2], M J Yang[2], H Lee[3] and R U Martinelli[3]; [1]Physics and Astronomy, University of Kansas, Lawrence, Kansas; [2]Naval Research Laboratory, Washington, District of Columbia; [3]Sarnoff Corporation, Princeton, New Jersey.

Recent efforts to improve the performance of mid-infrared antimonide-based semiconductor lasers have focused on enhancing the absorption of the pump beam to maximize power conversion efficiencies and minimize threshold intensities. One successful approach has been the optical pumping injection cavity (OPIC) laser, in which a type-II W active region is enclosed between distributed Bragg reflector (DBR) mirrors in order to achieve multiple passes of the pump beam and thereby to enhance absorption. Previously, fixed wavelength sources have been used for optical pumping of OPIC laser structures, with limited tuning available by adjusting the incident angle. By tuning the pump wavelength incident on an OPIC laser using an optical parametric oscillator, we demonstrate minimum threshold intensities and maximum slope efficiencies at the resonance of the DBR cavity surrounding the active region, further demonstrating the potential of OPIC lasers. A 3.2 μm OPIC laser operated at 350 K in pulsed mode (at the highest operating temperature of the dewar), with a characteristic temperature of 50 K. The power conversion efficiency at 300 K was the highest ever observed in the mid-IR, at approximately 5%. Results will be presented for two OPIC samples (emitting at $\sim$3.2 μm and 4.3 μm at high temperature), one of which was designed with a broadened cavity resonance, suitable for pumping with a multi-mode source. Threshold intensities and slope efficiencies measured as a function of pump wavelength demonstrate the strong resonance effect, and that the "broadened OPIC" does in fact manifest a much wider resonance than the non-broadened resonance cavity design.

4:00 PM Z4.8
Materials Considerations in Wafer Bonded Epitaxial Templates for GaAs/Si and InP/Si Heterostructures. James Michael Zahler[1], Anna Fontcuberta i Morral[1], Chang-Geun Ahn[1], Harry A. Atwater[1] and Mark Wanlass[2]; [1]Applied Physics, California Institute of Technology, Pasadena, California; [2]National Renewable Energy Laboratory, Golden, California.

Metal-free direct wafer bonding and layer transfer by hydrogen-induced exfoliation have been used to transfer thin films ($\sim$650nm) of both Ge(100) and InP(100) to Si(100) support substrates to fabricate Ge/Si and InP/Si heterostructures of $\sim$1cm^2 area. The bonded interface of heavily doped ($>1x10^{18}$ cm^{-3}) structures exhibits linear, low-resistance current-voltage characteristics with a measured specific resistivity of $<0.1\Omega\cdot$cm^2. The promise of these heterostructures as heteroepitaxial templates has been established by the MOCVD growth of optically active GaInP/GaAs/Ge/Si and InGaAs/InP/Si structures on wafer bonded Ge/Si and InP/Si templates respectively. These structures illustrate the potential of wafer bonding processes to enable the integration of epitaxially incompatible materials to form novel optoelectronic devices, including hign-performance multi-junction solar cells supported on low-cost, mechanically-robust Si substrates. In one application we are exploring the use of Ge/Si heteroepitaxial templates for the fabrication of a triple-junction solar cell structure consisting of GaInP, GaAs, and Ge subcells. In a second application we propose to use wafer bonding and layer transfer processes to design a process to fabricate a four-junction cell design with target efficiencies in excess of 40% by utilizing a wafer bonded InP/Si heterostructure to serve as an epitaxial template for subcells of InGaAs and InGaAsP. Subsequent wafer bonding would then be used to integrate this with a subcell structure consisting of GaAs and GaInP. While the optical activity of III/V semiconductors grown on Ge/Si and InP/Si heterostructures has demonstrated their potential as heteroepitaxial templates, TEM analysis of the MOCVD grown InGaAs/InP/Si structures indicates a large density of defects in the grown layer that propagate from the as-cleaved InP/Si surface, which contains a large micro-roughness and a large density of implant induced defects. Additionally, AFM studies of homoepitaxial Ge grown by MBE on as-cleaved Ge/Si heterostructures reveal surface a surface morphology consistent with defects in the epitaxial layer. Work in progress to be presented will focus on the exploration of processes to improve the surface morphology and remove defects from the growth surface of the wafer bonded heterostructures such as chemical mechanical polishing, wet or dry chemical etching, and buffer layer growth. The effects of these treatments on subsequent epitaxy will be studied.

4:15 PM Z4.9
The Effect of Chemical Laser Vapor Doping p+ Spike on the Barrier Height of PtSi/Si Heterostructure. Meicheng Li[1], Liancheng Zhao[1], Xuekang Chen[2] and Gan Wu[2]; [1]Materials Physics and Chemistry, Harbin Institute of Technology, Harbin, China; [2]Laboratory of Laser Molecular Beam Epitaxy, Lanzhou Institute of Physics, Lanzhou.

The structure PtSi/p+/p-Si by chemical vapor doping has been investigated for the sake of reduction of Schottky barrier height. The detail study of the effect of laser energy density, laser pulse number and partial pressure of impurity gas on the chemical laser vapor doping had been investigated. The results indicate that the threshold of doping boron using 248 nm KrF laser is 0.75 J/cm2, and the thickness of melting layer is conditioned with characteristic quantity, namely the thickness of doping is not related to the laser energy. Using the appropriate parameters, the 1 nanometer doping spike was grown by chemical vapor doping. The Schottky barrier height of PtSi/p-Si with the doping spike is 0.13 eV. It is lowered 0.06 eV than that of PtSi/p-Si without the doping spike. Since the Schottky barrier height is lowered, the cut-off wavelength could be extended. Due to the Fowler dependence, and the PtSi detector's quantum efficiency should been improved.

4:30 PM Z4.10
Feature Size and Density Effects in Wet Selective Etching of GaAs/AlAs p-HEMT Structures with Organic Acid – Peroxide Solutions. Vinay Subhash Kulkarni[1], Kanti Prasad[1],

William E. Quinn[2] and Frank H. Spooner[2]; [1]Electrical and Computer Engineering Department, University of Massachusetts Lowell, Lowell, Massachusetts; [2]Semiconductor, Skyworks Solutions, Inc., Woburn, Massachusetts.

Pseudomorphic HEMT (p-HEMT) devices are used in a number of wireless communication applications including power amplifiers in the 1-50 GHz range, low noise amplifiers and switches. Selective wet etching is often used to form the gate regions of these devices to avoid plasma damage associated with dry etching. We have investigated the wet etching of small ($8\mu m - 0.5\mu m$) features with organic acid – hydrogen peroxide solutions. Two acid solutions were used as a selective etchant for GaAs using AlAs etch stop layers in a p-HEMT structure grown by MBE. The etched features were characterized by AFM, SEM, and electrical FET measurements. The etch depth uniformity and reproducibility were found to depend on a number of factors including feature size, feature density, etching chemistry, agitation and surface tension. When features with a range of size and density were placed in close proximity in a layout we found that the etch rate of the different features was a function of density, size and most importantly the etch chemistry. One etchant solution exhibited a 12% difference in etch rate from the smallest feature to the largest, while another solution exhibited uniform etching of all features regardless of size or density. Both solutions produced specular etched surface in GaAs and AlGaAs. However, the AlAs etch stop showed a non-uniform surface morphology after etching. The surface morphology of the AlAs etch stop is one factor that limits the over etch which can be designed into the process. The most important factors to be considered in designing a selective etch process will be presented.

4:45 PM Z4.11
Investigation of electrical Properties for in-situ Deposited Ni Contact on 4H-SiC Using Synchrotron Photoemission Spectroscopy. Sang Youn Han and Jong-Lam Lee; Dept Materials Sci. & Eng., POSTECH, Pohang, Gyeongbuk, South Korea.

Silicon carbide (SiC) is a promising material for high power and high temperature electronic devices due to its superior intrinsic properties. Using Schottky-Mott theory, it is expected that the sum of the Schottky barrier height (SBH) to n- and p-type SiC would be equal to the energy band gap (3.26 eV). However, most of the earlier works have not satisfied this requirement and the factor that influence the Fermi level movement is not clearly understood. Thus, in-depth evaluations of interface chemistry and surface band bending upon the formation of interface in Ni/4H-SiC are necessary. The SiC wafers used in this study are both the n-, and p-type 4H-SiC single crystals. In order to remove carbon and oxygen contaminations on SiC surface, the SiC samples were in situ annealed (800 °C, 5 min). Then, Ni was deposited on the cleaned SiC surface using the thermal evaporator. The thickness of the Ni layer was determined using attenuation of the intensity in Si 2p spectra before and after the deposition. To find the interfacial reaction in Ni/SiC contact, Ni deposited samples were annealed at 600 °C for 1 min. These results were compared with electrical experiment in both types of samples. From these, the mechanism for the Schottky barrier formation of Ni/4H-SiC is discussed. At the as-deposited state, the Ni/n-SiC interface appeared to be abrupt and unreacted as evidenced by the constant FWHM of the Si 2p core level spectra before and after the deposition. For n-SiC, the SBH was estimated to be 1.6 eV, which agree well with the 1.66 eV of the Schottky-Mott theory. And the surface band bending upon the deposition of Ni increased. This is due to the high work function of contact metal (Ni) and indicates that Fermi level moved depending on the metal work function. However, for p-SiC, SBH was evaluated to be 1.0 eV, which is lower than theoretical value and the change of surface potential was not followed by the work function of contact metal, but influenced by the surface defect level. In addition, upon annealing the Ni/n-SiC, Ni reacted with SiC to form Ni silicide, leading to the increase of work function from secondary emission spectra. These suggest that the SBH could be enhanced with the formation of Ni silicide.

SESSION Z5: Poster Session
Chairs: F. Danie Auret and Anneli Munkholm
Tuesday Evening, December 2, 2003
8:00 PM
Exhibition Hall D (Hynes)

Z5.1
Raman Spectroscopy Study of The Novel Wide Band-gap Semiconductor $B_{12}As_2$. J. Pomeroy[1], M Kuball[1], N W A van Uden[2], H Hubel[2], D J Dunstan[2], J Chaudhuri[3], M Fayaz[3], R Nagarajan[4] and J H Edgar[4]; [1]H.H. Wills Physics Laboratory, University of Bristol, Bristol, United Kingdom; [2]Physics Department, Queen Mary, University of London, London, United Kingdom; [3]Mechanical Engineering Department, Wichita State University, Wichita, Kansas; [4]Department of Chemical Engineering, Kansas State University, Manhattan, Kansas.

Icosahedral boron arsenide ($B_{12}As_2$) is a novel wide band-gap semiconductor (~3.5 eV) which exhibits extraordinary self-healing properties when exposed to radiation. This property suggests a potential application in beta cells for the direct conversion of nuclear energy to electrical energy. We have used micro-Raman spectroscopy to gain insight into this novel wide band-gap semiconductor. Films grown by chemical vapour deposition on 4H and 6H SiC substrates were investigated. An As-As stretching phonon mode at 308 cm^{-1} can be seen strongly in X(ZZ)-X scattering geometry, but not in X(YY)-X. Other modes are attributed to As-icosahedra, inter- and intraicoshedral vibrations, apart from the 505 cm^{-1} mode whose origin is still unknown. The hydrostatic pressure dependence of $B_{12}As_2$ phonon frequencies was investigated using Raman spectroscopy and a diamond anvil cell. We have observed a weak pressure dependence for the 505 cm^{-1} mode (less than 0.5 cm^{-1}/GPa). This behaviour is consistent with previously reported measurements on the 525 cm^{-1} mode of α-rhombohedral boron, suggesting that these modes have a similar origin. The pressure dependence of the As-As stretching mode is about 2 cm^{-1}/GPa; inter- and intraicosahdral modes are found to have coefficients in the range of 3-6 cm^{-1}/GPa. The phonon frequency dependence on biaxial strain was determined using coordinated Raman spectroscopy and x-ray diffraction. The results provide insight into a new material with potential applications in wide band-gap devices and the ability to determine stress/strain using micro-Raman spectroscopy is beneficial to the development of future devices.

Z5.2
Soft x-ray spectroscopic analysis of three phases of Si_3N_4. Sam A Leitch[1], Alex Moewes[1], Wai-Yim Ching[2] and Toshimori Sekine[3]; [1]Department of Physics and Engineering Physics, University of Saskatchewan, Saskatoon, Saskatchewan, Canada; [2]Department of Physics, University of Missouri-Kansas City, Kansas City, Missouri; [3]National Institute for Materials Science, Tsukuba, Ibaraki, Japan.

Silicon nitride (Si_3N_4) is a very useful material in industry today. It's hardness, and resistance to oxidation make it promising for mechanical applications. In addition, the insulating or semi-conducting properties of this material have proven useful for solid-state electronic devices. α and β phases of this ultra-hard ceramic have been known for a while. The third, and highest energy γ phase, has only been realized within the last few years, and only in a purely polycrystalline form. γ-Si_3N_4 is harder than the previous two phases, and predicted to be a large-gap semiconductor. Analysis of the electronic properties of the α, β, and γ phases of Si_3N_4 were performed using synchrotron-based soft x-ray spectroscopy. Soft x-ray spectroscopy provides a means to directly probe the linear partial density of electronic states (LPDOS) of a material near the Fermi level. The techniques used are non-destructive, bulk sensitive, element specific, and sensitive to small changes in the electronic structure. From this analysis, a number of electronic properties can be derived, including band-gap, density of states, and complete band-structure, including spin. Each of the three phases of Si_3N_4 provides unique properties, which showcase the possibilities of these spectroscopic analysis techniques.

Z5.3
Electronic structure of native point defects in $ZnGeP_2$. Xiaoshu Jiang, Maosheng Miao and Walter R. L. Lambrecht; Physics, Case Western Reserve Universtiy, Cleveland, Ohio.

Ternary semiconductors with the chalcopyrite structure such as $ZnGeP_2$ are attractive for frequency conversion nonlinear optical applications in tunable mid infrared laser sources because of their high second order optical response coefficients and birefringence which allows for phase matching. However, point defects with undesirable optical absorption bands are limiting the performance. In this paper, we present a computational study of native defects in $ZnGeP_2$. Using fully structurally relaxed full-potential linear muffin-tin orbital local density functional 64 atom supercell calculations, we obtained energies of formation as function of the Zn and Ge chemical potentials and as a function of the Fermi level for the various possible charge states of V_{Zn}, V_{Ge}, Zn_{Ge}, and Ge_{Zn} point defects. Our calculations indicate that previous interpretations of the EPR AL1 center as the $V^-{}_{Zn}$ center need to be revised. In fact, EPR-ENDOR studies of this defect clearly indicate localization of the wave function on a pair of P atoms, in contrast with our calculations which show that the four surrounding P atoms participate equally in the V_{Zn} defect. No Jahn-Teller instabilities are expected for this defect, nor for the alternative candidate the Zn_{Ge} antisite based on the symmetry of the defect level in the gap. We propose a V_{Zn}-Ge_{Zn}-V_{Zn}complex as an alternative candidate for the AL1 center based on the low energies of formation of the compensating Ge_{Zn} donor and V_{Zn} acceptor in Zn-poor conditions, in analogy with a common defect complex in the

cousin material $CuInSe_2$. This model can naturally account for some of the outstanding symmetry and structural features of the EPR center. Work supported by AFOSR.

Z5.4
Fabrication of side-illuminated p-i-n Photodiode with waveguide layers. Byung Ok Jeon, Alan S.K. Yang, Hwa-young Kang and Do-Young Rhee; telecommunication R&D center, samsung electronics, Suwon, Gyeonggi-do, South Korea.

We present the fabrication of side-illuminated p-i-n photodiode. This is suitable for passive surface integrated on planar lightwave circuit (PLC), which are able to make the low-cost packages. Epitaxial structures have two main layers, diode layer and waveguide layer. It was determined by a beam propagation methode (BPM) simulation results. To get a high responsivity and reliability, each layer must be etched, so we called this photodiode "double etched waveguide photodiode". We carried out an experiment on various methodes and some devices were satisfactory for the optical communication system at 1.3- and 1.55 micrometer wavelenths. The alignment tolerances were included in the test results.

Z5.5
Intersubband transitions in GaN/AlGaN multiple quantum well structures. Omar Manasreh[1], Jie Liang[1], F. Xie[2], Steve Puntigan[2], Hadis Morkoc[2], L. He[2] and K. S. Ramaiah[2]; [1]Electrical Engineering Dept, University of Arkansas, Fayetteville, Arkansas; [2]Electrical Engineering Dept, Virginia Commonwealth University, Richmond, Virginia.

Molecular beam epitaxy grown GaN/AlGaN multiple quantum wells were investigated by using an optical absorption technique. Intersubband transitions were observed in several samples that were designed with either bulk Al0.35Ga0.65N or short-period GaN/Al0.65Ga0.35N superlattice barriers. The GaN wells were Si-doped with a doping level in the order of 10Î1cm-2. The 2-dimensional electron gas (2DEG) density estimated directly from the total integrated area of the intersubband transitions is found to be more than two orders of magnitude larger than the intentional Si-doping level. The large 2DEG density observed in the multiple quantum well samples is explained in terms of the polarization-induced charges formed at the GaN/AlGaN interfaces. This assertion was supported by the increase of the 2DEG density as the number of the GaN/AlGaN interfaces in the short period lattice barrier is increased. Simple calculations of the 2DEG density and polarization as a function of Al mole fraction were made and compared with the experimental measurements.

Z5.6
Effects of ZnTe/ZnTe:Cu Complex Back-Contact on Device Characteristics of CdTe Solar Cells. Lili Wu, Lianghuan Feng, Daolin Cai, Wei Cai, Jiagui Zheng, Yaping Cai, Bing Li, Wei Li, Jingquan Zhang and Qiang Yan; Department of Materials Science, Institute of Solar Energy Materials and Device,Sichuan university, Chengdu, Sichuan Province, China.

Zinc telluride is an ideal back-contact material for CdTe solar cells due to the small valence-band offset with CdTe and possibility of heavily p-doped by Cu, which means that a thin interlayer of Cu-doped ZnTe between p-CdTe and metal back electrode of high work function can make a stable and low ohmic contact. In order to prevent the diffusion of Cu atoms into CdTe layer and decrease the interface state densities between p-CdTe and Cu-doped ZnTe layers, we have proposed to introduce an un-doped ZnTe film as a buffer between both the layers. In this paper, ZnTe:Cu layers have been deposited by vacuum co-evaporation, and the CdTe solar cells with three kinds of back contact, i.e. complex ZnTe/ZnTe:Cu layer, single ZnTe:Cu layer and no buffer layer, have been fabricated. The influences of Cu concentration in the doped ZnTe layer as well as the thickness of un-doped and Cu-doped layers on I-V characteristics of these cells have been studied. Considering the abnormal temperature dependence of dark conductivity in ZnTe:Cu films, we have investigated the effects of annealing temperatures on the performance of the cells. The results show that the "roll over" and "cross over" phenomena of dark and photo I-V curves can be eliminated by use of the complex back-contact layer. In general, the performance of the cells with a complex layer is better than that with a single layer and much better than that without back contact layer. It has been demonstrated that the diode quality factor has decreased to 1.8 and the fill factor has increased to 73% for CdS/CdTe/ZnTe/ZnTe:Cu cells, in which there is no high resistance transparent layer. The relative reasons have been discussed.

Z5.7
CBD-ZnxCd1-xS Thin-Film and Its Application in CdTe Solar Cells. Jie Zhou[1] and Xuanzhi Wu[2]; [1]National renewable energy lab, golden, Colorado; [2]National renewable energy lab, Golden, Colorado.

Cadmium telluride has been recognized as a promising photovoltaic material for thin-film solar cells. In the conventional CdS/CdTe device structure, cadmium sulfide (CdS) has been most commonly used as a most successful window material. Higher short-circuit current density (Jsc) can be achieved by reducing the CdS thickness to improve the blue response. However, reducing the CdS thickness can adversely impact device open-circuit voltage (Voc) and fill factor (FF). Developing ZnxCd1-xS with higher band gap to replace CdS has been recognized as one of several techniques to reduce this issue. The solution technique was found to offer more advantages over vacuum evaporation and spray pyrolysis by formation of homogeneous, good crystallinity film. The higher solubility of ZnS compared to CdS and lower solubility of Zn(OH)2 compared to Cd(OH)2 make the deposition of ZnS as the dominate process. Phases of CdS, ZnS and alloy were all found in the solution deposited film. Considering the high efficiency CdTe cells with CdS window layer deposited by CBD, the ZnxCd1-xS alloy film formed from CBD was studied in this paper. Alloy films were prepared by deposition of thiourea in an alkaline solution containing cadmium and zinc salt. Ammonia was used as the suitable complextant to control the deposition of thiourea and avoid the formation of metal hydroxide. Thick films of around 800 A on tin oxide (SnO2) were achieved, which was thick enough to resist the consumption of window layer material during CdTe cell fabrication. XPS results show a zinc concentration of about 7 to 8% through the alloy film. Surface morphology and electric properties were compared with the CBD CdS film. According to the empirical correlation of optical band gap and material composition, the alloy was estimated to have band gap of 2.48 eV at this zinc concentration. However, the optical measurement indicates the band gap at 2.46 eV. Single alloy signal was not detected in the film by XRD. XRD signal of the alloy film did not show difference from the poly CdS film. It may be explained by the low zinc concentration, multiple phases and poor crystallinity of the as-deposit film. The ZnxCd1-xS film was tested in the CdTe cell. A ZnxCd1-xS/CdTe cell with an NREL-confirmed total-area efficiency of 15.7% was achieved (Voc=840.1 mV, Jsc=24.81 mA/cm2, and FF=75.55%). We believe that this is the best cell result when using ZnxCd1-xS window layer. The most interesting is that high Voc (>840 mV) and high FF (0.74-0.76) can be routinely reached. This may due the formation of a mix layer of ZnCdSTe in the junction, which reduce the lattice mismatch between the ZnxCd1-xS and CdTe films.

Z5.8
Abstract Withdrawn

Z5.9
Optical Characterizion of the Floating Gate-Channel Tied HEMT Photodetector for 1.0μm~1.6μm Photodetector Applications. Hongjoo Song, Youngchang Jo, Cheong Hyun Rho and Hoon Kim; Korea Electronics Technology Institute, PyungTaek-Si, South Korea.

We report the design, fabrication and optical properties of the modified In0.48Al0.52As/In0.53Ga0.47As high electron mobility transistors (HEMTs) for 1.0μm~1.6μm photodetector applications. The optical characteristics of HEMTs are demonstrated by photovoltatic effect. The built-in electric field in between In0.48Al0.52As and In0.53Ga0.47As separates the optically generated electron-hole pairs in the In0.53Ga0.47As channel or absorbing layer; the electron to the two dimensional electron gases (2DEGs) region, holes toward the channel-neutral region respectively. The holes with long life time and low mobility result in a significant charge build-up in the channel-neutral region, leading to the electron injection from the external circuit. This photogenerated voltage results in a large optical gain in HEMTs. The epi-structure for the modified HEMT photodetector consists of a 3000$\AA$-thick undoped In0.48Al0.52As buffer layer on semi-insulating Fe-doped InP (100) substrate, a 4000$\AA$-thick undoped In0.53Ga0.47As channel layer, 50$\AA$-thcik undoped spacer layer, Si δ-doped In0.48Al0.52As supplier, a 250$\AA$-thick undoped In0.48Al0.52As schottky barrier and 200$\AA$-thick Si-doped In0.53Ga0.47As cap layer. The Ni/Au/Ge/Ni/Au alloy and Ti/Pt/Au were used as ohmic and schottky gate contact respectively. In order to promote more optical gain, the modified HEMT photodetector is constructed by connecting the gate and channel so that the gate can be modulated by illumination. A contact hole for the connection of the gate to the channel is defined by wet-etching from shottky barrier to a portion of channel and subsequent lift-off of the gate metal. The optically accumulated holes in the channel-neutral region induce the positive charges to the gate tied into the channel and produce the extra photogenerated current. The optical properties of the modified HEMT photodetector including the optical gain, dark current and sensitivity depending on the device parameters will be demonstrated in detail.

Z5.10
Leakage and Electrical Interface Characterization of TiN/AlN/SiC MIS Devices. Brindha Nagaraj[1], R D Vispute[1], T

Venkatesan[1], D Habersat[2], Matt Ervin[2], Bruce Geil[2] and C J Scozzie[2]; [1]Department of Physics, University of Maryland, College Park,, Maryland; [2]Army Research Laboratory, Adelphi, Maryland.

SiC possesses all the right properties such as wide band gap, high electrical breakdown strength and other unique properties such as high melting point, high thermal conductivity, native SiO_2 layer, high electron drift velocity, high density and hardness to be used as a semiconductor in high power, high temperature and high frequency electronic device applications capable of operating in harsh environments. The complementary gate dielectric to be used with SiC is one of the central issues in successful device technology. SiC could also be of special interest, for similar reasons, namely that its native oxide is also SiO2. However, it appears that SiC/SiO_2 interface has poor electrical properties when compared to Si/SiO_2 interface. In the present work, the electrical, dielectric and interface properties of pulsed laser deposited and sputtered AlN is investigated for gate dielectric applications for SiC from the following points of view: a) Leakage level and mechanism, b) Dielectric constant and dielectric loss c) Insulator trap and hysteresis and d) Interface trap The leakage current is $\sim 20\mu A/cm^2$ at 300^0C and 100V. The mechanism of conduction in TiN/AlN/SiC-n type is found to be the interface limited Schottky emission. The dielectric constant of 600nm AlN film on SiC is $\sim$7 and improves towards the reported value of 8.5 in a 2μm thick AlN film indicating the presence of interfacial low dielectric constant dead layer. However, it is very encouraging to find the dielectric constant of AlN to be temperature and frequency independent.The capacitance-voltage plot shows considerable hysteresis indicating insulator and slow interface traps. In addition, the flat band voltage is $\sim$ 32V indicating a high interface state density of $\sim 10^{12}/cm^2$.It is found that the leakage, dielectric and interface properties improve with more rigorous surface preparation of SiC wafer prior to AlN deposition.

Z5.11
Novel operation of GaAs/AlGaAs quantum well field-effect phototransistor. Kwangsue Park, Yeon Shik Choi, Minjae Jung and Hoon Kim; NANO scale quantum devices Research Center, Korea Electronics Technology Institute, Pyungtaek-Si, Kyunggi-Do, South Korea.

A quantum well field effect phototransistor (QW-FEPT), highly sensitive to a near infrared (NIR) photodetector, was fabricated by using conventional high electron mobility transistor (HEMT) process technique. Single-, double- and triple QWs with a 10 nm thick GaAs well and 10 nm thick AlGaAs barrier layers grown by molecular beam epitaxy (MBE) had no defect on the layer by layer, which were demonstrated by transmission electronic microscopy (TEM) and photoluminescence (PL) measurements taken at 11 and 300 K. they were used for QW-FEPTs of which response on a NIR illumination was investigated. On the investigation of I-V measurements, all of the QW-FEPTs showed normal FET characteristic properties under dark condition. However, under illuminated condition (a monochromatic wavelength of 840 nm), peculiar hysteresis-curve-like properties were observed at room temperature under the bias voltage range of -0.5 $<$ Vds $<$ 0.1, of which I-V curves have a distinction as a function of increasing gate bias and they were converged and crossed on the both ends of the range. Moreover, photo-voltaic effect was observed from the samples. This photo-voltaic effect was outstanding in the triple QW-FEPTs compared to the single or double, the magnitude of measured negative voltage caused by the effect increased as increasing input optical power. Although the exact mechanism is not clear, it is considered that the internal reverse field is generated and affects on the QW channels. The novel photon-induced characteristic effect, which could be hardly observed in single or double QW-FEPTs, provides an enhanced photoconductivity in the operation of phototransistor by enhanced photocurrent due to the internal reverse bias effect. It can be suggested that the internal voltage giving reverse field effect is generated by the photo-voltaic effects due to the built-in potential induced by photon-assisted hole trapping in an accumulated layer and tunneling effect.

Z5.12
3C-SiC for high-speed integrated photonics.
Carlos Angulo Barrios, Christopher Ian Thomas, Michael Spencer and Michal Lipson; Electrical and Computer Engineering, Cornell University, Ithaca, New York.

In this work, we propose a compact 3C-SiC electro-optic modulator for high-speed silicon-based integrated optoelectronics operating at 1.55-μm fiber-optic communications wavelength. Cubic (3C or β) SiC has a crystal symmetry non-centrosymmetric that provides a large electro-optic coefficient, 2.7 pm/V at a wavelength of 633 nm. The Pockels effect allows high modulation speeds (on the order of tens of GHz). The high bandgap (2.2 eV) of 3C-SiC makes it suitable for waveguiding at the visible and near-infrared spectrum range. Due to its cubic structure, 3C-SiC is suitable to be grown on a Si substrate and it is compatible with the mature Si technology. A SiC-SiO2-Si [SiC-on-Insulator (SICOI)] platform is used for optical confinement in the normal direction to the propagation plane. The device is based on an optical microresonator using sub-micron size high-index-contrast SiC waveguides. We use the Pockels effect of 3C-SiC to change electrically the effective refractive index of the structure and obtain a high-speed phase modulation. The optical resonator converts this phase modulation into intensity modulation. Switching times on the order of 10-100 ps can be achieved with negligible power consumption.

Z5.13
Elevated Temperature Characteristics Of Carbon-Doped GaInP/GaAs Heterojunction Bipolar Transistor Grown By Solid Source Molecular Beam Epitaxy. Rong Zhang, Soon Fatt Yoon, Kianhua Tan, Zhongzhe Sun and Qingfeng Huang; Microelectronics, Singapore, Singapore.

This paper reports the characteristics of GaInP/GaAs heterojunction bipolar transistor (HBT) with carbon-doped GaAs base layer grown by solid source molecular beam epitaxy (SSMBE) using carbon tetrabromide (CBr4) as p-type dopant precursor. Hydrofluoric acid (HF) was used to passivate the GaInP/GaAs HBTs. At base bias voltages below 0.8V in the Gummel plot, the base current of large-area devices after HF treatment was greatly reduced. This indicates that the extrinsic base surface recombination current was greatly reduced. After HF treatment, detailed DC characterization of the device performance from 300K to 380K was carried out and the carrier transport properties were investigated. The base current and collector current ideality factors at 300K were 1.12 and 1.01, respectively. This indicates that the space- charge region recombination current in the base is insignificant. From the temperature- dependent Gummel plot, the activation energies of collector current and base current were obtained. For the collector current, the activation energy is 1.4eV, which is close to the bandgap of the GaAs base. This indicates that the collector current is determined by the drift-diffusion process, in which an energy barrier of the same magnitude as the base bandgap is to be overcome by electrons before they reach the collector. For the base current, the activation energy is also 1.4eV, which is close to the bandgap of GaAs, indicating that band-to-band recombination plays a dominant role in the base current. No trap-related recombination was observed for the base and collector currents, which further indicates the high quality carbon-doped GaAs base material for the HBT structures.

Z5.14
Analysis of Photoluminescence Efficiency in Annealed GaInNAs Quantum Well Grown by Solid Source Molecular Beam Epitaxy. Tienkhee Ng, Soonfatt Yoon, Weijun Fan and Shanzhong Wang; Electrical and Electronic Engineering, Nanyang Technological University, Singapore, Singapore.

Current high-speed optical communication systems require optical devices operating at 1.3 μm or 1.55 μm. So far, InP based lasers and detectors are the most popular devices for these purposes. However, considering the benefits of lower costs and robustness of GaAs substrates, GaAs-based optical devices would be a very attractive candidate. This is currently the research and development trend of high-speed data link optical systems. For example, the vertical cavity surface-emitting laser (VCSEL) formed with GaInNAs quantum well (QW) based laser, and grown on GaAs substrate has received considerable attention by the engineering and scientific communities. In this investigation, a double QW structure with a 7.5 nm GaInNAs QW and a 7.5 nm GaInAs QW was grown by a solid source molecular beam epitaxy (SSMBE) system. The system allows for an efficient incorporation of N and In at a low growth temperature of 450 degree Celcius. By evaluating the PL emission efficiencies of the QW within the temperature range of 4 K to 150 K, a dual-activation-energy model (DAE) was found to fit the results wel. A single-activation-energy (SAE) model, on the other hand, showed deviation from the experimental values at mid temperature range. One of the states obtained from the DAE model fitting is the localized state, and its activation energy of 9 meV was identified to be due to the energy difference between this state and e1 state. The other state has an activation energy of 38 meV and has a large quenching effect at temperatures higher than 100 K. In addition, the carrier dynamics of the localized state was further examined by decomposing the PL spectra into a low-energy and a high-energy Gaussian functions. The PL integrated intensities of the low-energy Gaussian function indeed showed the characteristics of carrier localization, and therefore validates the attribution of the 9 meV activation energy to be localized state related. This study suggests the GaInNAs QW room temperature PL emissions at 1.3 μm or 1.55 μm may be improved by minimizing or eliminating the localization effect

Z5.15
Laser Power and Temperature Dependent Photoluminescence Characteristics of an Annealed GaInNAs/GaAs Quantum

Well. Tienkhee Ng, Soonfatt Yoon, Weijun Fan and Shanzhong Wang; Electrical and Electronic Engineering, Nanyang Technological University, Singapore, Singapore.

Although GaInNAs-based laser grown on GaAs provides both low cost and robust substrate advantages compared to lasers grown on InP, the fundamental studies of the annealed GaInNAs QW PL mechanisms is still lacking. One of the issues concerns the fast quenching of the annealed GaInNAs QW at room temperature even though its 4.5 K PL efficiency increases after annealing. Such characteristic is undesirable for current 1.3 μm or 1.55 μm high-speed optical communication systems that require optical devices operating at room temperature. It is therefore important to study the carrier dynamics of the GaInNAs QW. This issue can be studied and explained by both PL and TRPL measurements. In the PL measurements, a 514.5 nm Ar-ion laser were used to excite the QW and the emitted PL signals were collected by a liquid N2 cooled Ge detector. In this investigation, a double QW structure was grown by a solid source molecular beam epitaxy (SSMBE) system, which allows efficient incorporation of N and In using a low growth temperature of 460 degree Celcius and V/III ratio of 20. The low growth temperature also prevents phase separation of these nitride materials as reported in the existing literature. In addition, SSMBE provides a much cleaner environment for hydrogen free growth ambient to efficiently eliminate hydrogen related defects that is found in metal-organic chemical vapour deposition systems. The photoluminescence (PL) measurements of an annealed GaInNAs quantum well (QW) with varying laser excitation intensity and temperature is studied to understand the low temperature photoluminescence properties of an annealed 6 nm GaInNAs QW. It is found from the laser-excitation-power dependent integrated PL intensity that localization effect is still existing in the QW even after annealing. This effect is characterized by an activation energy of 11 meV below the e1 state, which is obtained from fitting the integrated PL intensity vs. temperature curve with a single-activation-energy (SAE) model. This center is correlated to the main localization center below the e1 state as a results of N or In compositional fluctuation.

Z5.16
Crystal Growth and Characterization of InSbN Grown by Metalorganic Vapor Phase Epitaxy. Toshiyuki Ishiguro, Yuta Kobori, Yoshihito Nagawa, Yasuo Iwamura and Shigeo Yamaguchi; Electrical, Electronic and Information Engineering, Kanagawa University, Yokohama, Japan.

Electron moblity of InSb is higher larger than other III-V compounds semiconductors including GaN-based III-nitride semidonductors. To make use of such advantage in terms of a high-speed device, the problem of a large lattice-mismatch between InSb and GaAs has to be overcome. It has been reported that the lattice-mismatch of 14% between InSb and GaAs has a significant effect on the electrical properties of a InSb film grown on a GaAs substrate mainly because defects such as misfit dislocations generate in the interface. In terms of the improvement of the electrical properties of InSb hetero-epitaxial films, we have focused on the crystal growth of $InSb_{1-x}N_x$ from the standpoint of controlling the strain between GaAs and $InSb_{1-x}N_x$, which can be lattice-matched to GaAs. $InSb_{1-x}N_x$ films with a thickness of about 2 μm was grown on (001) GaAs substrates by the low-pressure metalorganic vapor phase epitaxy (LP-MOVPE). The pressure was set to be 100 Torr and the growth temperature was ranged from 400 to 500 °C. The θ-2θ X-ray diffraction analysis showed that two peaks were located at 2θ=56.79° and 57.48°. The former corresponds to lattice constant c (=6.484 Å) of (004) InSb, and the latter corresponds to c (=6.408 Å) of (004) cubic $InSb_{1-x}N_x$. Since InSb and InN are difficult to be miscible with each other, the two peaks were observed simultaneously. Using the values of lattice constants, the nitrogen content in $InSb_{1-x}N_x$ was estimated to be 0.053. In addition, the SEM observation showed that the incorporation of nitrogen was effective on the improvement of the surface morphology compared to that of InSb itself.

Z5.17
Strain Relaxation Modes of Hetero-epitaxial Layers on Mis-cut Substrates. Chong Cook Kim[1], K.W. Moon[1], P. Ruterana[2], Y.B. Kwon[3] and J.H. Je[3]; [1]Samsung Electro-Mechanics, Suwon, South Korea; [2]LERMAT, FRE 2149 CNRS-ENSICAEN, CAEN, France; [3]Materials Science and Engineering, Pohang University of Science and Technology, Pohang, South Korea.

The recent advances of Light emitting diodes and laser diodes are especially based on improved characteristics such as low-threshold current high-output power and reliability. The reduction of threshold current has been successfully achieved by incorporation of biaxial strain into the quantum wells. A reliable operation at high temperature is improved by employing mis-oriented substrates as well. However it is a challenging work to apply the benefits of strain-induced modifications to the valence band structures and mis-oriented substrates to device-quality layer growth. Introducing maximum possible strains with minimum misfit dislocation density needs to be compromised. Furthermore, in case of strained layer growth on mis-oriented substrates, high density of atomic steps on surface should be considered additionally. To improve both the performance and reliability, understanding of strain and relaxation mechanism on stepped surfaces is clearly needed. We studied the strain relaxation modes of intentionally strained GaInP layer of +1% lattice mismatch grown on mis-oriented GaAs substrates with AlGaInP buffer layer by metal organic vapor phase epitaxy. High resolution space maps using triple axis x-ray diffraction was used to examine the relaxation of the epitaxial layers in both perpendicular directions of [0 1 1] and [0 - 1 1]. We found anisotropy in strain relaxation. The 0.1 degree tilt of GaInP crystal axis to miscut direction of [0 1 1] was observed, while in the perpendicular direction of [0 - 1 1] the structure was well ordered. The relaxation induced micro cracks, which was dominant in step direction of [0 1 1], characterized by atomic force microscopy as well as in TEM. We attributed the anisotropy to surface steps caused by miscut. The steps play a precursor role in strain relaxation of heteroepitaxial layers. The strain-relaxation mechanism on stepped surfaces is discussed.

Z5.18
A Reflecting Mirror Facet (RMF) Photodiode Suitable for Surface-Mounting PLC Platforms. Seungkee Yang[1], Doyoung Rhee[1], Byungok Jeon[1], Hwayoung Kang[1], Jinwook Burm[2], Donghoon Jang[1] and Taeil Kim[1]; [1]Photonics Lab, Samsung Electronics Co. LTD, Suwon, South Korea; [2]Dept. of Electronic Eng., Sogang University, Seoul, South Korea.

We introduce reflecting mirror facet photodiodes (RMFPDs) with integrated beam-axis-converter that can be used on a PLC (Planar Lightwave Circuit) platform using flip-chip bonding. The suggested RMFPDs were for surface mounting and edge illumination applications. The RMFPD utilizes V-grooves formed on {111} crystalline planes on the bottom side of InP substrate and a conventional vertically illuminated photodiodes on the top side. Two (111)In plane V-grooves which have an angle of 54.5 dgree to the surface of InP compose a beam-axis-converter that changes a side-illuminated beam into a nearly vertical beam (95.9 dgree). The beam-converter approximately fixes the output beam position regardless of the incident beam position. Therefore the output beam position remains nearly constant as the wafer thickness varies, which results in a large vertical alignment tolerance. RMFPDs employ conventional InGaAs/InP based photodiode structure. The V-grooves were formed by anisotropic wet chemical etching using HBr-based solution. The etch depth was 60 µm and the V-grooves are 30 µm apart. Because RMFPDs uses the conventional vertical PD structure with demonstrated high performances, the RMFPD inherits the same reliability and the yield. The fabricated RMFPD showed a dark current less than 0.1 nA at -5 V of which active diameter was 50 µm. The responsivity was 0.95 A/W for 1.55 µm light. The measured vertical and horizontal coupling tolerances of the fabricated devices between 0.5dB loss points using single-mode fiber were as large as 10m and 29m, respectively. These characteristics are adequate for 1.25Gbps TRx module Platform which is using passive alignment.

Z5.19
Conformational Dynamics of Phenylene Rings in Poly(p-phenylene vinylene) (PPV) and Derivatives as Revealed by ^{13}C Magic-Angle-Spinning Exchange NMR Experiments. Rodrigo Fernando Bianchi[1], Antonio Carlos Bloise[1], Jose Roberto Tozoni[1], Debora Terezia Balogh[1], Roberto Franco[2], Alexandre Marletta[3], Roberto Mendonca Faria[1], Eduardo Ribeiro deAzevedo[1] and Tito Jose Bonagamba[1]; [1]Departamento de Fisica, Universidade de Sao Paulo, Sao Carlos, Sao Paulo, Brazil; [2]Departamento de Fisica, Universidade Estadual Norte Fluminense, Campos, Rio de Janeiro, Brazil; [3]Universidade Federal de Uberlandia, Uberlandia, Minas Gerais, Brazil.

Poly(p-phenylene vinylene) (PPV) has shown a great potential for electro-optical applications due to its electroluminescent and semiconducting properties.[1] Such properties are directly related with the polymer chain conformation and dynamics. Then, it is important to understand the local chain motions. In this work, three ^{13}C Solid-State Magic-Angle-Spinning (MAS) Exchange NMR techniques were used to study conformational dynamics of phenylene rings in PPV.[2] The standard 2D-MAS Exchange experiment [2] was used to identify exchange processes between equivalent and non-equivalent sites. Centerband-Only Detection of Exchange (CODEX) experiments [3] were applied to determine the amplitudes, flipping fractions and the activation energies of the phenylene ring flips and small-angle oscillations. It was found that, at -15 °C, (26 ± 3)% of the rings undergo 180° flips in the millisecond time scale, with average imprecision of (30 ± 5)° and activation energies of (23 ± 3)kJ/mol. Other (31 ± 10)% of the rings performs only oscillations with average

amplitude of $(9 \pm 2)^{\circ}$. These results [4] corroborate previous experimental data [5] and agree with recent ab initio calculations of potential energies barriers in phenylenevinylene oligomers.[6] A comparison between the local dynamics of PPV and its derivatives, such as MH-PPV and MEH-PPV, is also going to be presented. [1] F.C. Grozema, L.P. Candeias, M. Swart, P.T. van Duijnen, J. Wildeman, G. Hadziioanou, L.D.A. Siebbeles, and J.M. Warman (2002) J. Chem. Phys. 117, 11366-11378. [2] Z. Luz, P. Tekely, D. Reichert (2002) Prog. Nucl. Magn. Reson. Spectrosc. 4, 83-113 [3] K. Schmidt-Rohr, E.R. deAzevedo, T.J. Bonagamba (2002) Enc. Nucl. Mag. Reson. 9, 633-642. [4] E.R. deAzevedo, R.W.A. Franco, A. Marletta, R.M. Faria, T.J. Bonagamba (2003) J. Chem. Phys. 119 (in press) [5] J.H. Simpson, W.B. Liang, D.M. Rice, F.E. Karasz (1992) Macromolecules 25, 3068-3074. [6] R.B. Capaz and M.J. Caldas (2003) Phys. Rev. B 67, 205205/1-205205/9

Z5.20

Electrical Properties of β-$FeSi_2$/Si Hetero-Diode Improved by Pulsed Laser Annealing. Keiichi Tsuchiya, Noboru Miura, Hironaga Matsumoto, Ryotaro Nakano and Shin-ichiro Uekusa; Science and Technology, Meiji, Kawasaki, Japan.

β-$FeSi_2$ has been attracting a great deal of interest because of significant characteristics such as emissive semiconductor with a band gap of about 0.85 eV and large optical absorption coefficient of over 10^5 cm^{-1} (at photon energies > 1 eV). So this material is expected to be applied efficient solar cells and optoelectronics devices, which are compatible with present optical telecommunication system. There are a few reports β-$FeSi_2$/Si epitaxial layer structure has a good crystallinity, although many studies on β-$FeSi_2$ were reported. To improve the crystallinity, it is necessary to anneal at the high-temperature (more over 900 °C) and long-time (dozens hours). However, thermal annealing has the problem of composition deviation in the thin film as a result of thermal diffusion. For p-n junction interface, we think that high temperature process is disadvantageous method. In this study, we succeed to obtain β-$FeSi_2$/Si hetero-diode by excimer laser annealing (ELA). We found that ELA technique became possible to prevent thermal diffusion. β-$FeSi_2$ films were a prepared by pulsed laser deposition (PLD) on N-type Si (111) substrate under ultra high vacuum (10^{-5} Pa). Sintered tablets $FeSi_2$ (99.9 %) and extremely pure Fe tablets (99.999 %) were used as the source material. In-situ ELA was performed with ArF excimer laser. Substrate temperature in the preparation process is lower than 500 °C. The crystallinity of β-$FeSi_2$ was evaluated by the X-ray diffraction (XRD) measurement and reflected high energy electron diffraction (RHEED). With ELA, β-phase was observed with 10 to 100 pulses at minimum irradiation energy of 100 mJ/cm^2. Diode characteristics were also investigated by I-V and C-V measurements. Both of electrodes have taken 0hmic electrode. The forward current also enhanced with increasing of laser intensity. We report in detail on the above results that the experimental facts obtained from XRD and RHEED measurements.

Z5.21

Electric Field Microscopy and Secondary Electron Imaging of Double Stacking Faults in Heavily n-Type 4H SiC after Oxidation. B J Skromme[1], M K Mikhov[1], L Chen[1], R Wang[2], C Li[2] and I Bhat[2]; [1]Department of Electrical Engineering and Center for Solid State Electronics Research, Arizona State University, Tempe, Arizona; [2]ECSE Department, Rensselaer Polytechnic Institute, Troy, New York.

Thermal processing or oxidation of 4H-SiC with n-type doping above about $3x10^{19}$ cm^{-3} is known to produce spontaneous double Shockley stacking faults by the passage of two partial dislocations of Burgers vectors $(a/3)<10\text{-}10>$. The resulting region of 3C stacking order acts like a quantum well in the 4H matrix, with band offsets mainly in the conduction band. Electron transfer from the 4H matrix into this quantum well may play a role in driving the growth of the faults. Here, we describe evidence for electric fields associated with this charge transfer mechanism, using secondary electron imaging in a scanning electron microscope (SEM) and electric force microscopy (EFM) as experimental probes. The samples consist of lightly-doped epitaxial layers on substrates of resistivity in the 0.007-0.008 Ω-cm range, which were oxidized for 90 min. at 1150 °C. The quantum well regions intersect the wafer surface as straight lines, due to the 8° misorientation of the wafer from the c-axis. These intersections appear as bright lines in the SEM images, which we attribute to an increased secondary electron yield related to the negative charge in the wells. Imaging by EFM using a Digital Instruments Multimode AFM also yields clear images of the quantum well intersections, similar to the SEM images. Tapping-mode AFM images show linear surface topographic features related to these lines, in addition to more pronounced undulations that may be related to the observed surface buckling. The EFM images correspond to the linear topographic features but not to the undulations, ruling out any artifacts related to the topography. Pronounced triangular surface steps are observed in some cases, whose origin is under investigation. Additional data from room and low temperature photoluminescence and panchromatic room temperature cathodoluminescence is also used to characterize the faults.

Z5.22

Raman Spectra of $CuAlS_2$ Single Crystals Inside Homogeneity Region. B. V. Korzun[1], R. R. Mianzelen[1], V. Riede[2] and K. Bente[3]; [1]Institute of Physics of Solids and Semiconductors, Minsk, Belarus; [2]Institute of Experimental Physics II, University Leipzig, Leipzig, Germany; [3]Institute of Mineralogy, Crystallography and Materials Science, University Leipzig, Leipzig, Germany.

The I-III-VI_2 semiconductors compounds with chalcopyrite structure ($CuFeS_2$) have been successfully applied in thin films photovoltaic. To improve the device-use potential, further advances are needed in growth methods controlling the degree of perfection, defects, doping, and in characterization methods. Raman scattering can be effective to characterize these compounds, which often include different phases. In this paper Raman scattering measurements were performed in backscattering configuration at the room temperature using DILOR XY800 spectrometer and Ar-laser with 514,5 nm wavelength as a light source. $CuAlS_2$ single crystals used in this experiment were prepared by chemical vapor transport using iodine as transporting agent in evacuated and sealed silica ampoules. The starting materials for each composition were initially prepared by a melt growth method. The composition varied inside the homogeneity region in 0,25 molar part from 0,4975 to 0,5100 molar part of Cu_2S. The most intensive peak at about 313 cm^{-1} is associated with the A_1 mode of the chalcopyrite lattice vibration, originating from the vibration of chalcogens atoms in the <001> plane that is generally observed in the I-III-VI_2 chalcopyrite compounds. The intensity and sharpness of this peak confirm good quality of crystallinity. The others peaks from 50 to 550 cm^{-1} were determined and their nature is also discussed.

Z5.23

Differential Thermal Analysis of $Cu_2S-Al_2S_3$ System. B. V. Korzun[1], R. R. Mianzelen[1], K. Bente[2] and G. Kommichau[2]; [1]Institute of Physics of Solids and Semiconductors, Minsk, Belarus; [2]Institute of Mineralogy, Crystallography and Materials Science, Leipzig University, Leipzig, Germany.

In recent years growing interest has been shown to complex semiconducting compounds I-III-VI_2 (where I-Cu, Ag; III-Al, Ga, In; VI-S, Se, Te). These chalcopyrite semiconductors are considered to be possible candidates for application in photovoltaic and optoelectronic. The I-III-VI_2 compounds lie on the $I_2VI\text{-}III_2VI_3$ section of the I-III-VI ternary system. Many of these sections have been investigated, but the Al-containing quasibinary sections have not been studied to date. The aim of the paper was to investigate the Cu_2S - Al_2S_3 quasibinary system by differential thermal analysis (DTA) and X-Ray powder diffraction (XRD). 35 alloys of various compositions in the Cu_2S-Al_2S_3 system were prepared and investigated. The components of each 5-10 g samples were sealed under vacuum in a BN crucible to avoid the interaction of aluminum and quartz. To obtain alloys samples of the Cu_2S-Al_2S_3 system with repeatable composition is difficult so that a special technique of sample preparation was developed. The presence of phase transitions and their temperatures were determined from DTA with the accuracy of phase transition temperature determination of 2°C. The initial charges were powdered alloys of typical weight 1g. Al_2O_3 was used as reference material. The identity of thermal conditions of sample and reference material was reached by their placing into a high-temperature steel clamp. The heating rates were 2-3°C/min. The T-x phase diagram of the Cu_2S-Al_2S_3 system was obtained for the first time. The homogeneity regions of the $CuAlS_2$ and $CuAl_5S_8$ semiconductors compounds were established. $CuAlS_2$ ternary compound melts congruently because there is gentle maximum on the liquids near the stoichiometric composition.

Z5.24

Pulsed Laser Deposition From Elementary Sources for Production of Semiconductor PbTe Films with Intrinsic Conductivity. Arik G. Alexanian[1], Garegin A. Aleksanyan[1], Nikolay S. Aramyan[1], Hovsep N. Avetisyan[2], Karapet E. Avjyan[1], Romen P. Grigoryan[3], Ashot M. Khachatryan[1] and Arsham S. Yeremyan[1]; [1]Dept. of Semiconductor Electronics, Institute of Radiophysics & Electronics, Ashtarak, Armenia; [2]Institute for Physical Research, Ashtrak-2; [3]Yerevan Physics Institute, Yerevan, Armenia.

Compound semiconductor films of PbTe from elementary sources were produced by pulsed laser deposition on KBr, silicon, mica, and polycrystalline corundum substrates. Technological regimes (growth temperature, range of laser fluences, etc.) were determined for single-crystalline growth of films. Structural investigations confirm that the single-crystalline growth of films can be reached at significantly lower temperatures as compared with other known

deposition techniques. Such decrease in growth temperature leads to suppression of generation of point defects and to possibility of production of high-stoichiometry single-crystalline films with very small concentration of free carriers. The measurements of temperature dependence of conductivity and Hall measurements show that in the temperature range from 77 to 300 K the resistivity of samples changes on more than 5 orders (5 x 10^5 times) while this variation is 3 orders of magnitude for specially compensated samples reported to our knowledge. The spectral dependence of photoconductivity was also investigated and the energy bandgap is found in agreement with values reported in literature. The role of the classical size-effect on resistivity and mobility of carriers is evaluated.

Z5.25

Infrared Dielectric Properties of $In_{1-x}Ga_xAs$ Epilayers on InP (100). Nelson Rowell, Guolin Yu, David Lockwood and Philip Poole; National Research Council Canada, Ottawa, Ontario, Canada.

The concentration dependence of optical phonons in strained $In_{1-x}Ga_xAs$ epilayers grown on InP (100) by chemical beam epitaxy has been characterized with oblique angle polarized far-infrared reflectivity measurements. In this powerful method, the reflectance spectra contain sharp Berreman peaks exactly at the optical phonon frequencies. For radiation polarized in the plane of incidence (p-polarized), peaks for both the TO and LO phonons were observed. For s- polarization only the TO modes were observed. For heavily doped substrates the TO film phonons were observed as reflectance minima, whereas for lightly doped substrates they were seen as maxima. The measured spectra were curve resolved to separate the effects of the various phonon modes which included a GaAs-like longitudinal and transverse optic (LO and TO), a disorder induced, and InAs-like LO and TO phonons. These new results indicated the disorder induced mode to be TO-like. The dielectric response function and phonon frequency dependences for all modes were obtained versus Ga fraction for x from 0.2 to 0.7 and the latter showed a quadratic dependence on x over this range. The effects of strain on the phonon frequencies could then be evaluated.

Z5.26

Defects and Surfactant Action of Antimony on GaAs and $GaAs_{1-x}N_x$ on GaAs [100] by Molecular Beam Epitaxy. Weng Kwong Cheah, Weijun Fan and Satrio Wicaksono; Microelectronics Centre, Nanyang Technological University, Singapore, Singapore.

Low temperature (4.5K) photoluminescence (PL) measurements and two-dimensional [115] high resolution x-ray diffractometry (HRXRD) rocking curves of antimony (Sb) doped III-V-(N) compound semiconductors on GaAs grown by solid source molecular beam epitaxy (SSMBE) detects a antisite defect peak at 1017nm (~1.22eV) by As-Sb exchange, under As-rich conditions. The inhibited Sb incorporation which generates this defect is caused by the latency effect in surface coverage, largely affected by desorption effects, background pressure and Sb incorporation rate. The elimination of this defect can be a measure of the improvement in crystal quality of GaAs(N):Sb, seen from both PL and HRXRD. Sb flux greater than $1.3e^{-8}$ Torr is needed to invoke the surfactant effect in III-V dilute nitride MBE growth.

Z5.27

Carrier Localizaton in GaAsSbN/GaAs Quantum Wells. Jia Li[1], Sudhakar Bharatan[1], Kalyan Nunna[1], Liangjin Wu[1], Shanthi Iyer[1] and K. Bajaj[2]; [1]Department of Electrical Engineering, North Carolina Agricultural & Technical State University, Greensboro, North Carolina; [2]Department of Physics, Emory University, Atlanta, Georgia.

In this work, we have investigated the temperature dependence of PL spectra of GaAsSbN/GaAs SQW heterostructures. First evidence of carrier localization is observed from the inverted s-shape curve exhibited by the temperature dependence of PL energy both in as grown and annealed samples. The localization appears to be deeper in annealed samples. This is also consistent with the behavior of the PL intensity and linewidth variations with temperature in these samples. The temperature, above which the red shift begins in accordance with Varshni's relation, occurs at about 170K. This relatively high temperature suggests the presence of high density of possibly deep-localizing potential wells. A possible explanation of the nature of localization in these QWs will be discussed.

Z5.28

Recombination Parameters for Antimonide-Base Semiconductors Using RF Photoreflectance Technique. Ravi J Kumar[1], Ronald J Gutmann[1], Jose M Borrego[1], Partha S Dutta[1], Christine A Wang[2] and Gregory Nichols[3]; [1]Center for Integrated Electronics, Rensselaer Polytechnic Institute, Troy, New York; [2]Lincoln Laboratory, Massachusetts Institute of Technology, Lexington, Massachusetts; [3]Lockheed Martin, Schenectady, New York.

Radio-Frequency (RF) photoreflectance measurements and one-dimensional device simulations have been used to evaluate bulk and surface recombination parameters in doubly-capped 0.50 to 0.59 eV p-type InGaAsSb epitaxial materials. InGaAsSb lifetime structures with variable active layer thicknesses are used to extract the surface recombination velocity (SRV), while samples with different active layer doping concentrations have been used to determine the Auger and radiative recombination coefficients. RF photoreflectance measurements and analysis are compatible with a radiative recombination coefficient (B) of approximately 3 x 10^{-11} cm^3/s, Auger coefficient (C) of 1 x 10^{-28} cm^6/s and surface recombination velocity (SRV) of $\sim 10^3$ cm/s or lower for 0.50 to 0.59 eV doubly-capped p-type InGaAsSb epitaxial layers.

Z5.29

Acceptors in undoped gallium antimonide. M. K. Lui[1], C. C. Ling[1], X. D. Chen[1], K. F. Lee[2] and K. W. Cheah[2]; [1]Physics, The University of Hong Kong, Hong Kong, Hong Kong; [2]Physics, Hong Kong Baptist University, Hong Kong, Hong Kong.

$V-{Ga}Ga-{Sb}$ has been considered to be the residual acceptor of GaSb responsible for the p-type conduction for the undoped material. However, in a recent studies of undoped GaSb (Ling et al 2002), Ga vacancy related defect revealed by positron lifetime spectroscopy disappears after $300{o}C$ annealing while the hole concentration of the sample remains nearly unchanged at about $10{17}cm{-3}$. This implies, at least for the samples annealed at $300{o}C$ or above, Ga vacancy related defect is not the only acceptor responsible for the p-type conduction. In this study, we are going to investigate the acceptors in the as-grown and the electron irradiated undoped GaSb with the use of temperature dependent Hall TDH measurement and photoluminescence PL. The effect of annealing will also be investigated. Ling et al, Appl. Phys. Lett. 80, 3934 (2002). AKOWLEDGEMENT This study is supported by the RGC, HKSAR (project no. 7107/02P)

Z5.30

Undoped gallium antimonide studied by positron annihilation spectroscopy. S. K. Ma[1], C. C. Ling[1], H. M. Weng[2] and De Sheng Hang[3]; [1]Physics, The University of Hong Kong, Hong Kong, Hong Kong; [2]Modern Physics, University of Science and Technology of China, Hefei, China; [3]Physics, Nanjing University, Nanjing, China.

Positron annihiltion spectroscopy has been used to study the vacancy type defects in undoped gallium antimonide. Temperature dependent positron trapping into the Ga vacancy in the as-grown sample was observed. Model will be constructed to describe the physics of this temperature effect. Annealing studies of electron irradiated sample were also performed to investigate the defect evolution upon annealing. ACKNOWLEDGEMENT This study is supported by the RGC, HKSAR (project no. 7107/02P)

Z5.31

The Influence of GaSb Layer Thickness on the Bandgap of InAs/GaSb Type-II Superlattices for Mid-Infrared Detection. Heather J. Haugan, Gail J. Brown and Frank Szmulowicz; Material & Manufacturing Directorate, Air Force Research Laboratory, Wright-Patterson AFB, Ohio.

The effect of GaSb layer thickness on the energy band gap (or cut-off wavelength) and photoresponse bandwidth of InAs/GaSb type-II superlattices for mid-infrared detections has been investigated on molecular beam epitaxy grown samples using 40 repeats of 20.5 Å InAs/0.7 ÅInSb-interfaces/X Å GaSb, where X ranged between 18, 21, 24 and 27 Å, while the InAs layer thickness was held fixed. The InSb-like interface was inserted between the layers to balance the superlattice strain. In photoconductivity measurements, we observed an increase of the energy band gap from 255 to 299 meV (the decrease of the cut-off wavelength at 50 % response ranged from 4.55 to 4.03 μm) and a decrease of the photoresponse bandwidth at treshhold as GaSb layer thickness varied from 18 to 27 Å. These experimental trends can be explained by an 8x8 envelope function approximation calculation that included the effect of in-plane asymmetry at InAs/GaSb interfaces. The results show that heavy holes are largely confined in the GaSb layers, while electron wave functions ovelap considerably from one InAs layer to another. As GaSb layers become narrower, the heavy hole-drived top of the valence band is pushed down in energy; at the same time, the overlap between the electron wave functions increases, resulting in increased conduction bandwidth, which in turn explains the increased photoresponse bandwidth. With increasing bandwidth, the bottom of the conduction band is pushed down in energy faster than the heavy hole band, thus the band gap narrows. Based on this theoretical modeling, one way to reduce the cut-off wavelengths and sharpen the photoresponse treshhold is to

increase the GaSb layer thickness.

Z5.32
Abstract Withdrawn

Z5.33
Synthesis of ternary SiGeSn semiconductors on Si(100) via Sn_xGe_{1-x} buffer layers. John Tolle[1], Matt Bauer[1], Cole Ritter[1], Peter Crozier[3], Jose Menendez[2] and John Kouvetakis[1]; [1]Chemistry and Biochemistry, Arizona State University, Tempe, Arizona; [2]Physics and Astronomy, Arizona State University, Tempe, Arizona; [3]Center for Solid State Science, Arizona State University, Tempe, Arizona.

Single-phase $Si_{1-x-y}Ge_xSn_y$ alloys with random diamond cubic structures are created on Si (100) via ultrahigh vacuum chemical vapor deposition reactions of SnD_4 with SiH_3GeH_3 at 350 °C. Commensurate heteroepitaxy is facilitated by $Ge_{1-x}Sn_x$ buffer layers, which act as templates that can conform structurally and readily absorb the differential strain imposed by the more rigid Si and Si-Ge-Sn materials. The crystal structure, elemental distribution and morphological properties of the $Si_{1-x-y}Ge_xSn_y/Ge_{1-x}Sn_x$ heterostructures are characterized by high-resolution electron microscopy, including electron energy loss nanospectroscopy, x-ray diffraction (rocking curves) and atomic force microscopy. These techniques demonstrate growth of perfectly epitaxial, uniform and highly aligned layers with atomically smooth surfaces and monocrystalline structures that have lattice constants close to that of Ge. Rutherford backscattering ion channeling shows that the constituent elements occupy random substitutional sites in the same average diamond cubic lattice and the Raman shifts are consistent with the lattice expansion produced by the Sn incorporation into SiGe tetrahedral sites.

Z5.34
Deep Levels in Multilayer Structures of $Si/Si_{0.8}Ge_{0.2}$ Grown by Low−Pressure Chemical Vapor Deposition. Yutaka Tokuda and Kenichi Shirai; Department of Electronics, Aichi Institute of Technology, Toyota, Japan.

Deep levels in multilayer structures of $Si/Si_{0.8}Ge_{0.2}$ grown by low-pressure chemical vapour deposition (LPCVD) have been characterized by deep level transient spectroscopy (DLTS). Thermal stability of deep levels in the layers was also investigated in the low temperature range up to 120°C. A 3 μm Si buffer layer was grown at 850°C on n-type (100) silicon with resistivities of 0.05−0.5 Ωcm and then ten periods of $Si_{0.8}Ge_{0.2}$ (5 nm)/Si (16 nm) were grown at 595°C followed by a 0.25 μm Si cap layer. These layers were doped with phosphorus. Schottky contacts were fabricated on the Si cap layer by thermal evaporation of gold. Isochronal annealing of 10 min was carried out for fabricated diodes at temperatures of 60, 90 and 120°C. DLTS measurements with the time constant of 18.5 ms revealed one dominant peak at around 130 K with a minor peak at around 240 K. The energy level for the dominant peak is estimated to be Ec − 0.20 eV from the Arrhenius plot of the emission time constants. This Ec − 0.20 eV peak increases in intensity during annealing up to as low as 120°C although the DLTS data could not be taken at higher annealing temperatures because of the degradation of diode characteristics. We speculate that the increase of intensity upon annealing is caused by the release of hydrogen incorporated during growth from defects. This leads to the instability of devices fabricated by LPCVD using SiH_4 and GeH_4 as precursor gases, PH_3 as a dopant gas and H_2 as a carrier gas.

Z5.35
Self assembled Au nano-dots in highly conducting ZnO matrix grown on epi-GaN/Sapphire. Amit Chugh, Asutosh Tiwari, Chunmin Jin, Haiyan Wang and Jagdish Narayan; Materials Science and Engineering, North Carolina State University, Raleigh, North Carolina.

We have studied the nature of epitaxy, defects and the heterostructures of ZnO-Au films grown on epi-GaN/sapphire substrates and also the structural, optical and electrical properties of aligned Au nano-dots in these ZnO films. These films were grown heteroepitaxially on epi-GaN/sapphire (0001) substrates by Pulsed Laser Deposition (PLD). High-resolution transmission microscopy (HRTEM) and X-Ray diffraction studies revealed high-quality epitaxial growth of ZnO matrix and Au nano dots. These Au nanodots were found to have the following epitaxial relationship (111) $_{Au}$ ∥ (0002) $_{ZnO}$ with in-plane orientation relationship of [110] $_{Au}$ ∥ [2-1-10] $_{ZnO}$. Electrical resistivity measurements showed these films to be highly conducting with a room temperature resistivity of about 2.5 mΩ-cm. Room temperature photo luminescence studies also indicate high optical quality of these films presumably due to the close lattice match and stacking order between ZnO and GaN. These heterostructures demonstrate the feasibility of integrating them with optoelectronic devices.

Z5.36
Improved Defect Tolerance of Quantum Dot Structures: A Comparison with Quantum Wells. Matthew Lamberti, Vadim Tokranov, Alex Katsnelson, Michael Yakimov and Serge Oktyabrsky; School of NanoSciences and NanoEngineering, University at Albany-SUNY, Albany, New York.

Quantum Dots (QDs) are expected to have superior properties when compared with quantum wells (QWs). One area of interest has been the improved defect tolerance of QD media. In this study the defect tolerance of nanoengineered QD structures is compared with that of a QW structure. Nanoengineering technology is based on the adjustment of a GaAs overlayer thickness prior to an additional heating step leading to QD truncation. The active layers were embedded into double heterostructures for effective collection of photogenerated carriers. There were two main steps in the experiment. First, the structures were bombarded with 1.5 MeV protons in order to introduce defects. Second, variable temperature photoluminescence (PL) was used to measure the degradation of the luminescence efficiency in the irradiated samples. We have found that the triple-layer (3x) QD structures can withstand one order of magnitude higher defect density than the 7xQD and two orders higher than the QW. A kinetic model was used to describe the radiative and non-radiative transitions as well as capture and thermal evaporation processes. The higher defect tolerances of QDs are associated with a stronger localization of carriers in the nanoengineered QDs than in the QWs. The 3xQD ensemble with strong localization also demonstrated the highest thermal stability as the gain laser medium up to 60 0C.

Z5.37
Surface Pattern Evolution During Thermal Cl_2 Etching of GaAs. Jens H Schmid, Richard Mar, Anders Ballestad and Tom Tiedje; Department of Physics and Astronomy, University of British Columbia, Vancouver, British Columbia, Canada.

In-situ thermal Cl_2 etching in combination with molecular beam epitaxial regrowth is a promising technique for the fabrication of novel GaAs/AlGaAs nanostructures; however, to be able to use the etch as a nanofabrication process one has to understand the evolution of a patterned surface during etching. We have used atomic force microscopy and light scattering measurements to investigate the morphological evolution of both flat and textured GaAs (001) surfaces during thermal Cl_2 etching at 10^{-4} Torr and a substrate temperature of 200°C. We find that the development of surface roughness on the flat substrates is in good quantitative agreement with a continuum model for the surface height. Experiments with microfabricated gratings (3 μm pitch, 100 nm amplitude) show that the crystal anisotropy of the etch rate limits the pattern transfer to etch depths of less than 1 μm unless the grating is oriented along the [100] crystal direction in which case the pattern can be transferred to etch depths of more than 3 μm. The transfer for gratings along the [110] direction can be improved by the use of a directional molecular beam of Cl_2 rather than exposure to a non-directional gas phase. The optimized pattern transfer is explained by a numerical model that takes into account the anisotropic etch rates and the spatial inhomogeniety of the Cl_2 flux to the surface. Characteristic asymmetric grating shapes develop during etching with a molecular beam at off-normal incidence. A new model consisting of two coupled differential equations for the Cl_2 concentration on the surface and the surface height reveals that the asymmetry is due to surface diffusion of the Cl2 molecules with a diffusion length of 60 nm.

Z5.38
Synthesis of Aligned ZnO Hexagonal Nanorods and Its Application to ZnS Based DC Electroluminescent Devices. Takashi Hirate, Hironori Tanaka, Shinya Sasaki, Tomomasa Satoh, Sinya Sasaki, Makoto Ozawa and Weichi Li; Electrical, Electronics and Information Engineering, Kanagawa University, Yokohama, Japan.

We succeeded in preparing the ZnO layer that was composed of the ZnO nanorods separated with each other on the p-Si wafer by the low-pressure thermal CVD method using O2 and metal Zn vapor as the precursors. The deposition conditions are as follows. The deposition temperature is 550 [°C]. The deposition pressure is 26.6 [Pa]. The O2 flow rate is 1.0 [SCCM]. The evaporation temperature of Zn is 580 [°C]. The deposition time is 15 [min]. The axis of the ZnO nanorod is the c-axis according to the XRD analysis and well-aligned in the direction perpendicular to the substrate. The shape of the nanorod is a hexagonal prism with a flat top. The height of the nanorod is about 2 [μm] and the distance between opposing edges of the hexagon of the top is about 100 [nm]. The separation between adjacent nanorods is about 200 [nm] in average. The ZnS:Mn layer of the thickness of 0.9 [μm] and the ITO electrode (2 [mm] in diameter) are then deposited on the ZnO layer by the electron beam deposition to prepare the ITO/ZnS:Mn/nr-ZnO/p-Si device. The ZnS:Mn layer is deposited not only on the top surface of the ZnO nanorod but also on

the side surfaces in some depth from the top edge using the electron beam deposition equipment in this study. Thus the top surface of the ZnS:Mn layer become almost continuous when the ZnS:Mn thickness is 0.9 [μm]. The concentration of Mn in ZnS is about 2 [at.%] according to the EDX analysis. When the +DC voltage is applied to the ITO electrode of this device, the current increases by 2 orders comparing with the device without the ZnO layer at the same applied voltage and the electroluminescent characteristics is observed. The electroluminescence spectrum is same as that of the ZnS:Mn reported so far having the peak wavelength at 580 [nm]. When the applied DC voltage is 300 [V], for example, the current density is 3 [mA/cm^2] and the luminance is 90 [cd/cm^2]. This electroluminescence is very stable and we consider this is a promising DC electroluminescent device. We estimate that the stable operation of this device is due to the current pass in the ZnO layer. The current is confined in the ZnO nanorods and does not spread in the lateral directions. The ZnO nanorod may operate as the stable current limiting element. This device is interesting as an application of the ZnO nanorods.

Z5.39
Ferromagnetic Mn Doped AlN Films Grown By Molecular Beam Epitaxy. Hongxue Liu[1], Stephen Wu[1], Lin Gu[3], Rakesh Singh[1], L. Budd[1], Mark van Schilfgaarde[1], David Smith[3,2], Nathan Newman[1], C. Stampfl[4] and A. J. Freeman[4]; [1]Department of Chemical and Materials Engineering, Arizona State University, Tempe, Arizona; [2]Department of Physics, Arizona State University, Tempe, Arizona; [3]Center for Solid State Science, Arizona State University, Tempe, Arizona; [4]Department of Physics and Astronomy, Northwestern University, Evanston, Illinois.

Dilute magnetic semiconductors (DMSs) offer a unique opportunity for the monolithic integration of ferromagnets and conventional semiconductors. The report of ferromagnetism in Mn doped GaAs above 100 K has aroused intense interest by the Spintronic community. Ferromagnetism above room temperature is, however, needed for most applications of interest. Our recent local spin density approximation (LSDA) calculations have predicted that III-nitrides doped with certain amounts of transition metal Mn or Cr could have a Curie temperature above room temperature. In this paper, we present the successful growth of high quality ferromagnetic Mn doped AlN films. X-ray diffraction (XRD) and TEM characterizations indicate that the AlN grows epitaxial on the SiC substrate, without evidence of secondary phase. Rutherford backscattering spectroscopy (RBS) and secondary ion mass spectroscopy (SIMS) indicate that the Mn distribution with depth is generally homogeneous. X-ray photoelectron spectroscopy (XPS) is used to determine the chemical nature of Mn in AlN. The magnetic properties of the film were carried out in a superconducting quantum interference device (SQUID) magnetometer with the magnetic field applied parallel to the sample plane. Clear saturation and well-defined hysteresis loop were observed between 10 K and 300 K, indicating that the films are ferromagnetic in this temperature range. The magnetization decreases very slowly as the temperature is increased from 10 K to 350 K. This suggests a Curie temperature well above room temperature. The observed magnetic characteristics are very similar to those of our recently reported Cr doped AlN films, suggesting that the observed ferromagnetism can also be attributed to a single magnetic phase in the films.

Z5.40
Characterization of zinc oxide single crystal for epitaxial wafer applications. Naoki Ohashi[1], Takeshi Ohgaki[1], Shigeaki Sugimura[1,2], Katsumi Maeda[2], Isao Sakaguchi[1], Haruki Ryoken[1], Ikuo Niikura[2], Mitsuru Sato[2] and Hajime Haneda[1]; [1]Electroceramics Group, National Institute for Materials Science, Tsukuba, Ibaraki, Japan; [2]Tokyo Denpa Co., Ltd., Tokyo.

Zinc oxide (ZnO) is a member of wide band gap semiconductor and it is characterized its high binding energy of exciton. There are a lot of prior studies for electric and optical properties of ZnO. For example, optically pumped laser of ZnO has been achieved in the last century and transparent field effect transistors made of ZnO and its alloys are one of the hot topics in current technology for display devices. Another interesting feature of ZnO is that its lattice parameters are very close to those of gallium nitride (GaN). It is expected that ZnO can be epitaxial substrate for growing GaN and its related alloys. Thus, development in bulk single crystal growth of ZnO is one of the key technologies for optoelectronic engineering. Very recently, we have succeeded to obtain ZnO single crystals of 2 inches diameter by hydrothermal method. In the present study, we characterized the ZnO bulk single crystals grown by hydrothermal method and 2"ϕ ZnO epitaxial wafers. The characteristics of the hydrothermal ZnO are 1) high crystallinity with large crystallite size and high electric resistivity. In order to use bulk ZnO as epitaxial substrate for growing functional thin films, ZnO, GaN and so on, we have to maintain high crystallinity and to control electric resistivity. Particularly, reduction of electric resistivity is one of key technology for application of hydrothermal ZnO single crystals. Another issue for using ZnO substrate for the substrates, we have to control its surface morphology to obtain atomically flat surface. From these points of views, we examined effect of thermal treatments on crystallinity, electric conductivity and optical properties of hydrothermal ZnO. As a result of investigations, we obtained highly conductive ZnO single crystalline wafers ($\sigma > 10^2\ \Omega^{-1}\mathrm{cm}^{-1}$) and single crystal wafers having atomically flat surfaces. We will also mention about the optical properties of hydrothermal ZnO in relation with Li and hydrogen impurities. Moreover, we will mention about ZnO bulk single crystal wafers showing positive sign of Hall coefficient.

Z5.41
Epitaxial Nano Structure in MOCVD ZnO Films Observed by FESEM. Yuneng Chang, Chemical engineering, Lunghwa University of Science and Technology, Taoyuan, Taiwan.

Compound semiconductor zinc oxide (ZnO), with a wide band gap of 3.37 eV, is a optoelectronic material. ZnO films are used for UV wavelength LED, transparent conductive films in flat panel displays and surface acoustic wave (SAW) devices for its high conductivity and piezoelectricity. Compared with other deposition technologies, metal organic chemical vapor deposition (MOCVD) owns advantages as high throughput, conformal mapping over complex structure, and compatible with contemporary semiconductor processing line. This presentation will address the observation of (002) ZnO films with ordered nano structure by atmospheric pressure (APCVD) at 320°C, which is far below previous reported values. CVD was performed in a horizontal APCVD, with precursor Zn(acac)2 sublimed at 110°C, and deposition temperature from 320 to 440°C, with reactive sputtered ZnO buffer layer over Si(100) as substrates. XRD results show that ZnO films are polycrystalline and have grains oriented at (002), (100) and (101), and dspacing of 2.60 Å, 2.47 Å,2.81 Å. For deposition temperature below 360°C, ZnO films have a strong preferential orientation along (002). Field emission SEM observed ordered nanostructure developed within ZnO films grown in inert ambient or using H2O vapor. In CVD with 15 torr H_2O vapor as co-reactant, with deposition temperatures below 340°C, films are continuous, uniform morphology, and have dense structure composed by polyhedron shaped columnar grains. These fine grains have radii from 150 to 300 nm. It seems that in this process regime, (002) might be thermodynamic favorable for ZnO nucleation. The growth rate is faster along the (002) basal plane of ZnO unit lattice, and slower along the {110} prism planes. For temperature between 360 and 380°C, SEM shows film growth habit shifts to epitaxial morphology. Ordered hexagonal or circular shaped plate shaped grains, with edge length of 1-2 μm and 300 nm thick, was observed. Some grains were stacked together in a unit of several plates. This growth habit might originate from hexagonal facet in nucleation, and subsequent layer growth, Frank-van der Merwe mode, along (002) plane. Above 400°C, screw dislocation growth patterns as described by BCF model were observed. The terrace width and ledge height were estimated as 150 and 30 nm, respectively.

Z5.42
Magnetic properties of ZnO thin films co-doped with Co and P. Jeong Min Baik and Jong-Lam Lee; Materals Science & Engineering, POSTECH, Pohang, Kyungbook, South Korea.

Wide bandgap oxide magnetic semiconductors based on TiO_2 or ZnO have been considered as useful materials for magneto-optical device application. In particular, the magnetic ZnO-based DMS would be very useful because its high exciton binding energy (59meV). Recently, room temperature ferromagnetism has been observed in Mn- and Co-doped ZnO films. However, few reports have mentioned the change of magnetic property with the concentration of the p-type dopant such as gallium, nitrogen, and phosphorus in ZnO-based DMS. According to the theory of Hole-mediated ferromagnetism, the ferromagnetic property for the films will be stronger than that for undoped (Zn,Co)O films. In this paper, the effect of phosphorus doping on magnetic property of Co-doped ZnO films will be reported. All Co-doped ZnO thin films were deposited on Al_2O_3 (0001) substrates by magnetron co-sputtering method using ZnO and Co metal targets. 1−10 mol. % of P_2O_5 powders was added to enhance the hole concentration, followed by annealing at 1200 °C. Deposition was performed in a 20 mTorr Oxygen and Argon atmosphere with the base vacuum of 1×10^{-6} Torr. The substrate temperature was fixed at 500 °C. Magnetic properties of (Zn,Co)O films with P concentration by Superconducting quantum interference device magnetometer (SQUID) will be discussed. To investigate the effect of P doping on the magnetic property of the films, the microstructures (Synchrotron XRD) and optical properties (Raman, PL) of (Zn,Co)O films will be presented. The carrier type and concentration of the films will be addressed by Hall measurement. X-ray rocking curve data will be also presented to quantify the strain from Co incorporation during deposition. From these results, the origin of ferromagnetic properties in ZnO-based DMS will be discussed.

Z5.43
Determination of the Nitrogen Acceptor Ionization Energy in ZnO by Photoluminescence Spectroscopy. Lijun Wang, N Y Garces, L E Halliburton and N C Giles; Physics Department, West Virginia University, Morgantown, West Virginia.

Zinc oxide (ZnO) is a wide band gap semiconductor material. It is presently receiving considerable attention because of its potential for short-wavelength optical devices. To make efficient ZnO light emitters, one must have good control of both n-type and p-type doping. It is relatively easy to make highly n-type ZnO by doping with Al, Ga, or In. However, usable and reproducible p-type doping is still one of the crucial issues in ZnO research (this problem is made worse because of the high n-type carrier background in typical ZnO). Identifying a suitable p-type dopant is an important first step. In our present investigation, we have used photoluminescence (PL) and electron paramagnetic resonance (EPR) techniques to study nitrogen acceptors in ZnO. The bulk ZnO crystals used in this study were grown at Eagle-Picher (Miami, OK) by the seeded chemical vapor transport method. Small concentrations of nitrogen were present in the undoped crystals and larger concentrations of nitrogen were present in the crystals grown with N_2 added to the gas stream. In undoped as-grown crystals, no N^0 acceptor EPR signal can be photoinduced. After annealing an undoped crystal at 600°C, an N^0 acceptor EPR signal can be easily photoinduced. Temperature dependent PL experiments performed on both undoped and doped as-grown crystals indicate that the emission band at 3.216 eV is donor-acceptor pair (DAP) recombination and the emission band at 3.232 eV is an electron-acceptor (e, A^0) transition (both involving nitrogen). At 5 K, the (e, A^0) transition is not observed in the undoped as-grown crystal, but it can be observed in the 600°C annealed crystal. The (e, A^0) transition is much stronger in an N_2-doped as-grown crystal. The intensity of the (e, A^0) transition correlates well with the EPR intensity of the photoinduced N^0 acceptor. An ionization energy of (209 ± 2) meV is determined for the N^0 acceptor in ZnO by a detailed lineshape analysis performed on the (e, A^0) transition from 5 K to 100 K. In comparison, magnesium (Mg) is currently the most technologically important p-type dopant for GaN. The ionization energy of N^0 in ZnO is even smaller than that of Mg in GaN (~225 meV), which indicates that nitrogen is a very promising candidate for p-type doping in ZnO. This work was supported by the Air Force Office of Scientific Research (Grant No. F49620-02-1-0254).

Z5.44
Photoluminescence of ZnO thin film grown on ion-beam-induced α-Al_2O_3(0001). Jong-Yong Park[1], Yu. A. Ermakov[2], Hyung-Jin Jung[1], Ji-Won Choi[1], Jin-Sang Kim[1] and Won-Kook Choi[1]; [1]Thin Film Materials Research Center, Korea Institute of Science and Technology, Seoul, South Korea; [2]Moscow Institute of Radio Engineering, Moscow.

α-Al_2O_3(0001) single crystal surface is irradiated by N_2^+ at beam potential 300 eV in the ion dosage range $5x10^{15}$/cm^2-$1x10^{18}$/cm^2 at room temperature. After ion bombardment, chemical bonding on the modified sapphire surface was investigated by x-ray photoelectron spectroscopy. Below $1x10^{16}$/cm^2, only non-bonded N1s peak at the binding energy 398.7 eV was found, but Al-O-N bonding was found up to $2x10^{17}$/cm^2 which was located around 403 eV. As the ion dosage was increased up to $1x10^{18}$/cm^2, the occurrence of Al-N bonding was identified at the dose higher than $5x10^{17}$/cm^2 at 396.6 eV. II-VI ZnO thin film was grown on untreated/ion-beam-induced sapphire surface. ZnO thin films were deposited by UHV rf magnetron sputter and pulsed laser deposition. For investigating of the substrate effect, modified sapphire having Al-O-N bonding only, and both Al-O-N and Al-N bonding were used respectively. Initial formation of facet structure and photoluminescence will be discussed at each condition.

Z5.45
Structural, Optical and Electrical Characteristics of $Zn_{1-x}M_xO$ (M: V, Cr, Mn, Fe, Co, Ni).
Shivaraman Ramachandran, Ashutosh Tiwari, Chunming Jin and Jagdish Narayan; Materials Science and Engineering, North CArolina State University, Raleigh, North Carolina.

We have succeeded in incorporating various transition elements (V, Cr, Mn,..) into the lattice of zinc oxide by a non-equilibrium deposition process of Pulsed Laser Ablation. Thin films of such materials were grown on sapphire (0001) substrate. To accomplish this, a pulsed KrF excimer laser was used to ablate $Zn_{1-x}M_xO$ targets, prepared by conventional solid-state sintering technique. Temperature and pressure were controlled to obtain a single-phase material in the films. High Resolution Transmission Electron Microscopy (HRTEM) and X-Ray Diffraction were employed to characterize these films structurally. Electrical resistivity measurements were done in the temperature range of 12-300K, which indicate the films to be quite conducting. Optical characterization of the films, performed using absorption / transmission and photoluminescence, shows significant shift in the peak position. This shift in the band gap varies as a function of both composition and temperature of growth. This suggests the presence of different amounts of the dopant in the parent lattice of ZnO. If harnessed fully these materials could provide an easy way to produce wide band gap dilute magnetic semiconductors with potential in the spintronics industry.

Z5.46
ZnO MOVPE Kinetics Studied by Gas Phase FTIR Spectroscopy. Yuneng Chang, Chemical engineering, Lunghwa University of Science and Technology, Taoyuan, Taiwan.

Zinc oxide, a II-VI compound semiconductor, has been proven to be an excellent optoelectronic material, with applications spending from nanolasers, short-wavelength LED, to transparent conductor. Recently, we demonstrated that in a ZnO MOVPE using zinc acetylacetonate as precursor, if sputtered ZnO coatings were used as buffer layer, with water vapor as co-reactant, ZnO films, with unique (002) orientation plane, could be grown at temperature as low as 320°C. In this study, we used gas phase transmission FTIR to monitor gaseous products from this VPE system, and tried to correlate the impact of process parameters on film structure and morphology. Gas IR results revealed that, acetylacetone ($C_5H_8O_2$, Hacac) with characteristic IR peak at 1624cm^{-1} can be observed for sublimation temperature reached 70°C. This indicated that zinc acetylacetonate precursor could be vaporized at temperatures below literature reported value. For deposition with 15 torr H_2O vapor fed as co-reactant, acetylacetone is the major product at temperature from 320 to 440°C. From 380 to 420°C, IR band of residual water vapor at 3500 cm^{-1} is the second intense. For temperature below 360°C or above 420°C, water vapor bands were almost absent in the spectra. It seems that, at such temperature range, water vapor was almost consumed. We found that, at temperature below 360°C or above 420°C, the IR peak of Hacac is stronger, while ZnO films were also thicker with larger grains. It seems the existence of H_2O IR peak might be a link to $Zn(acac)_2$ whether dissociated completely or not. As compared with $Zn(acac)_2$/oxygen IR study, $Zn(acac)_2$/ H_2O system always show much less amount of acetone and CO_2. Based on IR observation, an idealized reaction model was proposed as: $Zn(C_5H_7O_2)_{2(g)} + H_2O_{(g)} \rightarrow ZnO_{(s)} + 2\ C_5H_8O_{2(g)}$ (1) It seems that in H_2O using process, water vapor plays an aggressive role to dissociate precursor and free $C_5H_7O_2$ at temperature as low as 320°C. H_2O may also stabilized $C_5H_7O_2$ by hydrogenate it and form $C_5H_8O_2$ molecule. Thereby shift reaction even rightward.

SESSION Z6: Joint Session with N8 and T6: Quantum Dots and Wires: Structure, Spectroscopy and Transport
Chairs: Hedi Mattoussi and Andrew Norman
Wednesday Morning, December 3, 2003
Room 302 (Hynes)

8:30 AM *Z6.1
Nanowire Semiconductor Materials for Low-dimensional Physics and Applications. Lars Samuelson, Solid State Physics, Lund University, Lund, Sweden.

Self-assembly of quantum structures into zero-dimensional (quantum dot) and one-dimensional (nanowire) structures is becoming a very hot item in materials science as well as for what it may offer for basic physics and for nanoelectronic/photonic applications. In this talk I will first discuss the formation of quantum dots via the Stranski-Krastanow (SK) self-assembling growth mode which has allowed the study of highly ideal quantum dot structures for basic investigations of the physics of few-particle configurations and exciton phenomena in single quantum dots, as well as for their use in different quantum optics applications. By assembly of SK quantum dots for electrical addressing, it has been possible to fabricate tunneling devices in which electrons tunnel via the zero-dimensional states of the quantum dot as the active element or for electrons tunneling via double-dot artificial molecule structures. Very recently this more traditional approach to optical and electrical applications of quantum dots has been rivaled by the alternative approach to form quantum dots arranged inside one-dimensional nanowires. I will present optical properties of quantum dots inside nanowires as well as resonant tunneling via single quantum dots placed in-between tunnel barriers inside such nanowire structures. Direct comparison between SK-grown quantum dots and quantum dots formed inside nanowires will be made. This research is supported from the Swedish Research Council (VR) and the Swedish Foundation for Strategic Research (SSF). The presentation will be based on contributions from Werner Seifert and Magnus Borgstrom in MOVPE-growth, Soren Jeppesen, Jonas Ohlsson and Ann Persson in CBE-growth, Reine Wallenberg et al. in TEM-imaging, Anders Mikkelsen et al. in STM.imaging, Claes Thelander, Mikael Bjork, Tomas Bryllert and Thomas Martensson in

transport device studies, Valery Zwiller, Jonas Persson, Lars Landin, Nicolay Panev and Niklas Skold in PL-studies and Mats-Erik Pistol, Craig Pryor, Magnus Holm, Martin Persson and Hongqi Xu in theory/modelling.

9:00 AM Z6.2
Observation of Quasi-Periodic Twinning Superlattice in GaAs Nanowires. K W Adu[1], U J Kim[1], B K Pradhan[4], D Tham[3], D Yates[3], J E Fischer[3], U D Venkateswaran[5] and P C Eklund[1,2]; [1]Physics, Pennsylvania State University, University Park, Pennsylvania; [2]Materials Science & Engineering, The Pennsylvania State University, University Park, Pennsylvania; [3]Material Science and Engineering and LRSM, University of Pennsylvania, Philadelphia, Pennsylvania; [4]Commertial Technology, Columbia Chemical Company, Marietta, Georgia; [5]Physics, Oakland University, Oakland, Michigan.

A single material superlattice or "twinning superlattice" can have significantly different properties from the bulk. The structure does not suffer from interface degradation due to mismatch or incoherent electron scattering from defects that occur in a conventional superlattice. Theoretical investigations of the electronic band structure of such periodically twinned materials reveal a red shift in the band gap. For example, the twinning superlattice of Si exhibits a bandgap of 0.6eV, while the bandgap for the bulk is 1.1eV. We have used a simple thermal batch process to grow GaAs nanowires with an almost periodic twinning superlattice. As the wire diameter (d) ranges from 5nm to 100nm, the superlattice period decreases, e.g., at d=10nm diameter, a typical period would be ∼5 unit cells along the (111) growth direction. The photoluminescence (PL) spectrum exhibits 3 peaks at 300 K: a doublet (1072nm, 915nm) and weak peak at 580nm (bulk GaAs has bandgap PL at at 850nm). The doublet is identified with a redshift in the bandgap; the origin of the peak at 580 nm is not currently understood, and it becomes intense at T=30K. We observe an ∼ 11cm-1 downshift and a broadening of the LO and TO phonon modes relative to bulk GaAs via Raman scattering that is identified with a thermal broadening and phonon confinement effects. Also results of SEM, HRTEM and optical absorption will be presented. We believe that this simple synthesis route, if properly understood, might be used to fabricate perfectly periodic nanowire: GaAs twinning superlattice, and other twinned superlattice nanowires as well.

9:15 AM Z6.3
Optical Studies of Charged Single Self-Assembled Quantum Dots. Morgan E. Ware[1], Allan Bracker[1], Daniel Gammon[1] and David Gershoni[2]; [1]Naval Research Laboratory, Washington, District of Columbia; [2]Physics Department, Technion-Israel Institute of Technology, Haifa, Israel.

Semiconductor quantum dots have been viewed in recent years as attractive components for implementing quantum computation schemes [1]. In particular, the unpaired spin of an electronically charged semiconductor quantum dot is especially exciting, not only because of its relatively long spin dephasing time, but also because a single spin in a single dot can be controlled and measured optically [2]. Knowledge of the discrete energy spectrum of these dots is vital for any future progress in this field. We have grown InAs/GaAs self-assembled quantum dot samples by molecular beam epitaxy using an indium flush technique [3]. Submicron aluminum apertures created by electron beam lithography have been used as a shadow mask such that single quantum dots can be selectively excited and measured. In addition, we have employed this shadow mask as the metal contact of a Schottky diode structure, providing us the capability to control the charge state of the isolated quantum dot. By varying the bias across the diode and at the same time measuring the photoluminescence from the dot, we precisely control and identify the charge states of the dot [4,5]. By analyzing the magnetic field dependence of the photoluminescence we can fully characterize the degeneracy of these charge states [6] and their polarization selection rules. The basic understanding of this system will be discussed as it provides the groundwork for further studies of more complex systems. [1] D. Loss, D. P. DiVincenzo, Phys. Rev. A 57, 120 (1998). [2] D. Gammon et al., Phys. Rev. Lett., 86, 5176 (2001). [3] Z. R. Wasilewski, S. Fafard, and J. P. McCaffrey, J. Cryst. Growth 201/202, 1131 (1999). [4] R.J. Warburton, et al., Nature, 405, 926, (2000) [5] D.V. Regelman, E.Dekel, D.Gershoni, et al., Phys. Rev. B 64, 165301, (2001) [6] J.G. Tischler, A. S. Bracker, D. Gammon, Phys. Rev. B 66, 081310(R) (2002).

9:30 AM *Z6.4
Engineering Quantum Structures and their Behavior. Gregory J. Salamo, Physics, Univ of Arkansas, Fayetteville, Arkansas.

Recent clever techniques for fabricating nanosize materials, one-atomic-layer-at-a-time, have simultaneously opened the door to new physics, chemistry, biology, and engineering. Nanosize materials simply do not behave as the bulk. Indeed, the rules that govern the behavior of these tiny structures are not known and must be uncovered. Going smaller is a fantastic adventure opening a new frontier in science and engineering. So many of our ideas have come from a better understanding of nature, that the trend is sure to continue as we examine and view nature on a nanoscale. In this talk we will discuss our recent efforts to engineer shape, size, density, and position of nanostructures and of the interactions between them, and to develop a clear understanding of their optical and electrical behavior. While self-assembly is providing exciting quantum dot structures to explore, it is equally exciting to try to use the rules we uncover to encourage dot formation to take a desired path. Can we understand the formation of faceted nanostructures? Can we encourage or seed dot structures to form specific arrays? Is it possible to engineer greater homogeneity of dot shape and size? Can we design both the optical and electrical behavior of either individual or arrays of nanostructures? In this talk we will review our progress to answer these questions and discuss the possibilities and challenges ahead. For example, we will discuss the formation of individual faceted nanostructures as well as the fabrication of a vertically and laterally ordered QD stacks forming three-dimensional QD arrays. We will present results from the photoluminescence (PL) spectra from individual dots and discuss the role of such phenomena as the phonon bath. We will also discuss an investigation of the PL spectra from ordered arrays of QDs, both as a function of temperature and optical excitation intensity, which reveal both a lateral and vertical transfer of excitation. Moreover, we will present results that explore the tunneling law between quantum dots. As another example, we will discuss the importance of surfaces with high Miller indices, as a template to the formation of nanostructures as well as their potential role in determining the shape and increased size uniformity of the confined structures. Importantly, these observations lead to an even more basic question of when and why high index surfaces are stable. Indeed, we have found that in order to understand the origin of high index surfaces that bound nanostructures we have to study them directly. Yet in another example we will discuss the manipulation of surface reconstruction and a critical role that it can play in the selection of dot or wire nanostructures. Finally, we will discuss the many exciting opportunities that may be ahead although we expect and look forward to many surprises.

10:30 AM *Z6.5
Growth, Structure, And Optical Properties Of III-Nitride Quantum Dots. Hadis Morkoc[1], Arup Neogi[2] and Martin Kuball[3]; [1]EE and Physics, Virginia Commonwealth University, Richmond, Virginia; [2]North Texas University, Denton, Texas; [3]University of Bristol, Bristol, United Kingdom.

Quantum dots in conventional semiconductors have been explored for their many degrees of confinement resulting in unique density of states which are thought to lead to low laser threshold current, among other applications. In the case of GaN, an additional advantage is that the layer or layers of quantum dots will decouple the active layers to be studied from the substrate or buffer layer and, thus reduce number of extended and point defects, because they would nucleate on dislocated regions. In this vein, GaN dots have been grown on c-plane sapphire and (111) Si substrates by reactive molecular beam epitaxy. A method involving two-dimensional growth followed by a controlled annealing during which dots are formed was employed. Due the dot nature and large dot density, relatively high luminescence efficiencies were obtained on both substrates. Single layer dots were used for AFM analysis whereas 30 layer dots were used for photolumiscence experiments. AlN barrier layers, some too thick for mechanical interaction, some thin enough for vertical coupling were used. Strong polarization effects lead to a sizeable red shift, which depends on the size of the dots. Optical processes in these quantum dots will be discussed in detail.

11:00 AM Z6.6
Diffuse X-Ray Scattering of InGaAs/GaAs Quantum Dots. Rolf Koehler[1], Michael Hanke[1], Daniil Grigoriev[1], Martin Schmidbauer[1], Peter Schaefer[1], Udo Pohl[2], Roman Sellin[2], Dieter Bimberg[2], Nikolai Zakharov[3] and Peter Werner[3]; [1]Institute of Physics, Humboldt-University Berlin, Berlin, Germany; [2]Insitute of Solid State Physics, Technical University Berlin, Berlin, Germany; [3]Max-Planck-Institute of Microstructure Physics, Halle, Germany.

Strained self-organised InGaAs/GaAs(001) quantum dots (QDs) are presently subject of intense research efforts due to their promising potential for optoelectronic device applications. We will report about structural investigations on five-fold stacks of $In_{0.6}Ga_{0.4}As$ QDs within a GaAs matrix grown by means of metalorganic chemical vapor deposition. The GaAs spacer thickness between the subsequent QD layers amounts to 20 nm, a thickness at which vertical QD correlation is believed to vanish, however, cross-sectional transmission electron micrographs (TEM) reveal a pronounced vertical correlation, whereas no lateral ordering could be observed in plan-view images. Applying highly strain sensitive high resolution x-ray diffraction in vicinity of

different reciprocal lattice points we provide a non-destructive access to the detailed QD shape and local strain status within the QDs and the surrounding matrix material. Since the expected diffuse signal will be extremely weak all measurements were carried out at synchrotron beamlines. Scattering simulations are based on a dynamical treatment within the framework of Distorted Wave Born Approximation. The strain field which enters the simulation procedure has been calculated by finite element method. Grazing incidence diffraction (GID) near the (200) and (020) reciprocal lattice points did not show any significant difference between the [100] and [010] directions. A similar shape isotropy was found with respect to [110] and [1$\bar{1}$0], proving an at least four-fold lateral QD symmetry. Moreover, scattering simulations regarding various dot shapes clearly indicate prismatic QDs with a flat top rather than pyramides. The mean lateral QD distance significantly influences the diffuse scattered intensity in GID geometry. Thus, we could deduce a value of approximately 80 nm, which corresponds well to the QD density of about 2E10 cm^{-2} estimated from plan-view TEM.

11:15 AM Z6.7
THz Manipulation of Excitonic Levels in Single InAs Quantum Dots. Frederik F. Schrey, Thomas Mueller, Gottfried Strasser and Karl Unterrainer; FKE, Vienna Univ. of Technology, Vienna, Austria.

The energy spacing of electronic states in self-assembled quantum dots (QDs) coupled with efficient electron capture capabilities into these discrete states predestine dots to be used as MIR photodetectors, emitters and turns them into candidates for q-bit operations. In contrast to subband transitions in two-dimensional structures the density of states is sharply peaked at the transition energy, which reduces the phase space for scattering. Therefore we expect longer relaxation and dephasing rates in QDs compared to quantum wells. A strong requirement for q-bit applications is the knowledge about a possible radiative coupling between the electronic levels. In our experiments we superimpose a pulsed NIR excitation laser field with a low intensity cw THz field on a single quantum dot. The dot is separated from other dots by etching a micropillar structure into the GaAs matrix. Furthermore the pillar structure allows a more efficient coupling to the THz radiation. The exciton recombination is recorded with a micro luminescence (PL) setup for NIR excitation as well as for combined NIR/THz excitation. First results show an electron transfer from the lower excitonic levels into higher levels, which changes the count rates for the emission lines. The efficiency of this process seems to depend on the NIR pump intensity and is object of further studies. Furthermore ultrabroadband MIR time-domain spectroscopy allows us to study the dynamical properties within the electronic dot levels. In a first approach we study the electron capture respectively injection into the electronic levels of dot ensembles. Combined with the micro-PL system we want to investigate the dynamics of electrons in single dots. We hope to gain knowledge of the relaxation and dephasing processes and to achieve coherent excitations within the electronic dot levels, which would allow very fast control of QD based devices.

11:30 AM Z6.8
Near-Field Magneto-Potoluminescence of Single Self-Organized Quantum Dots. Alexander Mintairov[1], James Merz[1], Alexei Vlasov[1] and Alexander Govorov[2]; [1]University of Notre Dame, Notre Dame, Indiana; [2]Physics and Astronomy, Ohio University, Athens, Ohio.

We present measurements of Zeeman splitting and diamagnetic shifts of single self-organized InAs/AlAs, InAs/GaAs and InP/GaInP quantum dots using low temperature (10K) near-field scanning optical microscopy with spatial resolution <200 nm, operating at magnetic field strengths up to 10 T. The measurements allow us distinguish dots of different sizes, atomic content and homogeneity and attribute their specific structural properties, with their magneto-optical properties. For InAs/GaAs and InAs/GaAs QDs we found an increase of the diamagnetic coefficient from 0.4 to 15 meV/T2 with increasing emission energy. This corresponds to an increase of the QD size from 5 to 10 nm. This observation is quite unexpected and implies lower In content for larger dots, compensating the usual quantum confinement effects. We estimated the difference in In composition between small and large dots to be quite large, approximately 40%. For InP/GaInP QDs we observed an anomalous behavior of the Zeeman splitting dependence on the initial value of magnetic field. When the magnetic field is swept from 10 to 0T, the spin splitting shows oscillatory behavior and it does not vanish at zero magnetic field. We interpret this observation to involve an internal effective magnetic field induced by polarized nuclear spins via the hyperfine interaction. Interestingly, the single InP dots with non-zero splitting typically have broad line widths. This fact suggests that the broadening can come from the interaction between the exciton and nuclear spins.

11:45 AM Z6.9
Evidence of Aharonov-Bohm effect on neutral excitons in type-II quantum dots. Evaldo Ribeiro[1], Alexander O Govorov[2], Wilson de Carvalho Jr.[1] and Gilberto Medeiros-Ribeiro[1]; [1]LNLS, Campinas, SP, Brazil; [2]Department of Physics and Astronomy, Clippinger Research Labs, Ohio University, Athens, Ohio.

By allowing a charged particle to circulate a confined magnetic field flux region, Aharonov and Bohm showed in 1959 that, surprisingly, there exist effects of the vector potential on the charged particles moving outside the magnetic field region. After following the circular path the particle wavefunction acquires a phase that is proportional to the magnetic flux contained within the closed path. For these effects to exist, phase coherence is mandatory. All observable phenomena depend only upon the magnetic flux Φ through the excluded region, and are shown to be periodic with period $\Phi_0 = hc/e$. This oscillatory characteristic is the signature of the Aharonov-Bohm (AB) effect. It is commonly believed that the AB effect is a typical feature of the motion of a charged particle interacting with the electromagnetic vector potential. Here we present a magnetophotoluminescence study of type-II InP/GaAs self-assembled quantum dots, unambiguously revealing the AB type oscillations for neutral excitons when the hole ground state changes its angular momentum from $l_h = 0$ to $l_h = 1$, 2, and 3. Although forbidden, the transitions from the electron ground state to higher angular momenta hole states reflect a broken symmetry for this island system. This can be understood in terms of the anisotropy of the islands revealed in both Atomic Force Microscopy experiments on uncapped islands as well as polarization dependent photoluminescence spectra. In addition to that, due to the fact one does not have a hard wall confining potential, a spillage of the electron and hole wavefunctions out and into the islands can be anticipated. The wavefunction overlap can be inferred from the photoluminescence intensity, and revealed a complex behavior which could be understood by the successive adjustments of the wave function lobes to the non-uniform edges of the island, being more sensitive at higher magnetic fields. The hole ring parameters derived from a simple model are in excellent agreement with the structural parameters determined for this system.

SESSION Z7: Joint Session with T7: Quantum Dots and Wires: Devices
Chairs: Pallab Bhattacharya and Zhiming Wang
Wednesday Afternoon, December 3, 2003
Room 208 (Hynes)

1:30 PM *Z7.1
Quantum Dot Lasers and Amplifiers. Udo W. Pohl and Dieter Bimberg; Institut fuer Festkoerperphysik, TU Berlin, Berlin, Germany.

Self-organized formation of quantum dots (QDs) upon heteroepitaxial growth of highly strained semiconductor layers has gained enormous importance for a novel generation of opto-electronic devices. The electronic and optical properties of such nanostructures are more similar to those of atoms than of solids (1). A decade after the prediction that a laser using active QDs should be superior to classical lasers e.g. with respect to decreased threshold current, high temperature stability and high gain, the first QD laser was demonstrated by us in 1993. Since then we developed new concepts for strain engineering and interface control to define QD size and density and to reduce losses. Today we have actually achieved unique device performance for both, edge and surface emitting QD lasers grown using MOCVD and MBE. InGaAs/GaAs QD edge emitters show an ultralow threshold for infinite length of 18A/cm^2 at 1.16 μm for threefold stacked dot layers, an optical output power exceeding 10 W, and internal loss below 1.5 cm^{-1}. We measured relaxation oscillations at 6 GHz, demonstrating the potential for cut-off frequencies above 10 GHz. For 1.3 μm emission, lasers with J_{th} = 70 A/cm^2 and 3 W cw output power were realized. As to surface emitters, we presented the first GaAs VCSEL based on QDs operating at 1.3 μm with 1.2 mW cw output power and more than 50% slope efficiency. Thus GaAs-lasers can now replace InP-based ones at least in the range up to 1.3 μm, and the potential exists to extend the range up to 1.55 μm. First results on MOCVD growth of lasers using organic group V-precursors as replacements for highly toxic hydrides are very promising. After demonstrating QDs with a high density and excellent optical quality, we realized edge emitters with a transparency current below 30 A/cm^2, 91% internal quantum efficiency and 2.2 cm^{-1} internal loss. Using alternative precursors, we demonstrated the first electrical VCSELs grown using MOCVD, having similar data at 1.1 μm as the MBE-grown VCSELs presented above. Semiconductor Optical Amplifiers based on QDs show gain recovery times as short as 100 fs, much faster than QW-based ones, indicating the potential of QDs for a novel class of devices with large commercial importance for multi-tera bit metropolitan area networks. Unusually long phase relaxation times of excitons in QDs of more than 600 ps make QDs presently the best candidates as backbone of optical computers. This work was performed in cooperation with N.N.Ledentsov, J. Lott, V.

Ustinov, R. Sellin, C. Ribbat. P. Borri, J. Hvam, U. Woggon, F. Hopfer and others. (1) D.Bimberg, M.Grundmann, N.N.Ledentsov: Quantum Dot Heterostructures, J. Wiley, Chichester 1999.

2:00 PM Z7.2
1.5 micron InAs quantum dot lasers based on metamorphic InGaAs/GaAs heterostructures. Victor M. Ustinov[1], Alexei E. Zhukov[1], Alexei R. Kovsh[1], Nikolai A. Maleev[1], Sergei S. Mikhrin[1], Alexei P. Vasil'ev[1], Ekaterina V. Nikitina[1], Elizaveta S. Semenova[1], Natalya V. Kryzhanovskaya[1], Yurii G. Musikhin[1], Yurii M. Shernyakov[1], Mikhail V. Maximov[1], Nikolai N. Ledentsov[1,2], Dieter Bimberg[2] and Zhores I. Alferov[1]; [1]Ioffe Institute, St. Petersburg, Russian Federation; [2]Institut fur Festkorperphysik, Technische Universitat Berlin, Berlin, Germany.

1.5 micron range emission has been realized using the InAs quantum dots embedded into the metamorphic InGaAs layer containing 20% of InAs grown by MBE on a GaAs substrate. This significant decrease in the matrix band-gap is presumably the reason for the increase in the quantum dot luminescence wavelength. Growth regimes were optimized to reduce significantly the density of dislocations propagating into the active layer from the lattice mismatched interface. 2 mm long InGaAs/InGaAlAs lasers with 10 planes of quantum dots in the active region showed threshold current density about 1.4 kA/cm2 with the external differential efficiency as high as 38%. Lasing wavelength depends on the optical loss being in the 1.44-1.49 micron range at room temperature. On the increasing the temperature the wavelength reaches 1.515 micron at 85C while the threshold current characteristic temperature of 55-60K was estimated. High internal quantum efficiency (?>60%) and low internal losses (?=3-4 cm-1) were realized. Maximum room temperature output power in pulsed regime as high as 5.5 W for 100 micron wide stripe was demonstrated. Using the same concept 1.3 micron InGaAs/InGaAlAs quantum well lasers were fabricated. The active region contained quantum wells with high (∼40%) indium content which was possible due to intermediate InGaAs strain relaxation layer. 1 mm stripe lasers showed room temperature threshold current densities about 3.3 kA/cm2 (?=1.29 micron) and 400 A/cm2 at 85K. Thus, the use of metamorphic InGaAs layers on GaAs substrate is very promising approach for increasing the emission wavelength of GaAs based lasers. However, quantum dot lasers demonstrated superior performance as compared to that of quantum well lasers even the latter having much shorter emission wavelength. This is probably due to the three-dimensional quantum confinement of recombination region in quantum dot structures which drastically reduces carrier spreading and the probability of non-radiative recombination on dislocations.

2:15 PM Z7.3
Nanoengineered Quantum Dot Active Medium for Thermally-Stable Laser Diodes. Vadim Tokranov, Michael Yakimov, Alex Katsnelson, Matthew Lamberti and Serge Oktyabrsky; School of NanoSciences and NanoEngineering, University at Albany - SUNY, Albany, New York.

With a goal of development of an efficient active layer for laser diodes operating at elevated temperatures, we have studied the influence of an overgrowth procedure on the properties of multiple-layer self-assembled InAs quantum dot (QDs) using photoluminescence, transmission electron microscopy (TEM), and electroluminescence. Optical properties of QDs were optimized by shape engineering through the adjustment of a GaAs overlayer thickness prior to a heating step, which has introduced truncation of pyramid-shaped QDs. TEM micrographs of these QD structures has confirmed that the employed growth procedure results in a truncated (flat top) pyramidal shape of QDs. We have also compared QD and multilayer QD structures with and without a few-monolayer-thick AlAs capping layer. The optical properties of InAs QDs capped by AlAs were found to have a strong dependence on truncation height. Both single-layer and in particular multilayer QDs with AlAs capping have demonstrated up to 15 meV larger energy separation between the ground state and the first excited state as compared to QDs without AlAs capping. Triple-layer truncated QD structure with AlAs capping showed 94 meV separation between ground state and first excited state. We believe that AlAs capping in combination with truncation procedure result in significant suppression of carrier transport between QDs within the layer as well as between QD layers. A record high characteristic temperature for lasing threshold, T_o = 380 K up to 55 °C, and maximum ground state lasing temperature of 219 °C were measured for 1.22 μm edge-emitting laser with this triple-layer truncated QD gain medium.

2:30 PM Z7.4
First electrically injected QD-MCLED emitting at 1.3 μm, grown by metal organic chemical vapour deposition. Vittorianna Tasco, Adriana Passaseo, Maria Teresa Todaro, Milena De Giorgi, Massimo De Vittorio, Iolena Tarantini and Roberto Cingolani; NNL-National Nanotechnology Laboratories, INFM, Lecce, Italy.

Microcavity light emitting diodes (MCLEDs) operating at 1.3 μm are suitable as telecom sources by virtue of single mode beam profile, low divergence output for optical fibres coupling, and vertical emission suitable. As opposed to the more expensive and temperature sensitive InP technology, the Stranski-Krastanov self-assembling technique allows the fabrication in the same epitaxial run of 1.3 μm emitting InGaAs/GaAs QDs and of high efficiency GaAs/AlAs distributed Bragg Reflectors (DBR) QDs growth techniques using molecular beam epitaxy (MBE) have already demonstrated high efficiency devices at the emission wavelength of 1.3 μm, such as room-temperature (RT) continuous-wave operation in-plane lasers. On the other hand, very few works are reported about 1.3 μm emission from metal-organic chemical vapour deposition (MOCVD) grown QDs. This problem, due to the increased density of coalesced QDs correlated to the increased strain and complicated surface environment, becomes more important when QDs are grown on a DBR structure. In this work we present the first electrically driven QD-MCLED operating at 1.3 μm and grown by MOCVD. The device shows an efficient and very narrow RT electroluminescence emission centred at 1.3 μm, obtained under a very low injection current. The MCLED structure consists of a bottom mirror, formed by n-doped GaAs/AlAs DBR, designed for a reflectivity of 93 %, and a p-doped top mirror designed with a reflectivity of 82%. A single layer of In0.5Ga0.5As QDs, directly grown on GaAs, is inserted in the centre of the GaAs one wavelength-thick cavity. The morphological analysis of the DBR surface and of the free-standing QDs, grown on the bottom DBR, has been carried out by Atomic Force Microscope (AFM). The optical and electrical behaviour of the device has been investigated by photoluminescence (PL) and electroluminescence (EL) measurements. The RT PL emission of a reference sample, where the InGaAs QDs have been directly grown on a GaAs layer, shows 1.3 μm emission with a full width at half maximum (FWHM) of 24 meV and clear band filling dynamics. The PL intensity quenches by a factor of 3 as the temperature is increased from 10 K to 300 K. A detailed study of the bottom DBR surface morphology has led to the optimal conditions for InGaAs/GaAs QD growth over the mirror. They show, indeed, a larger FWHM of 31 meV (exactly centred at the reflectance stop band), demonstrating a slightly lower size uniformity of the InGaAs islands, due to the higher surface roughness of the DBR structure. Both PL and EL measurements performed on the micro-cavity embedding the QDs inside two DBRs, show a very efficient RT emission at 1.3 μm with a FWHM of 6 meV and a Q factor of 150. The temperature quenching is less than a factor of 6.

3:15 PM *Z7.5
Self-Assembled Nanostructures and Quantum Devices In InGaAs/GaAs and InAs/InGaAlAs/InP. Wang Zhanguo, Wu Ju and Zhao Fengai; Key Lab of Semiconductor Materials Science, Institute of Semiconductors, Chinese Academy of Sciences, Beijing, China.

Self-assembled In (Ga) As/GaAs, InAlAs/AlGaAs/GaAs, and InAs/InAl (Ga) As/InP quantum dots (QDs) and/or quantum wires (QWRs) of free defects have been successfully fabricated using SK growth mode and MBE in our lab. Through adjusting the strain distribution of strained layer by optimizing growth condition, properly choosing component of InxGa1-xAs QDs, and introducing a special seed layer etc., the size, shape, and density of QDs with emission wavelength ranging from about 700 nm to 2 micrometer can be controlled. The room temperature CW lasing at 960nm with maximum output power of 3.62 W and the lifetime of more than 4000hrs for the multiplayer InGaAs/InAs/GaAs QDs active layer is realized. In addition, the multiple stacked self-assembled InAs dots have been made use of as the active region of a superluminescent diode, and above 200mW continuous wave output with the spectral bandwidth of 60nm is obtained at room temperature. In order to reduce the irregularity arising out of atomic processes during MBE growth, it is required to understand the underlying mechanisms of the various growth morphologies in these dot- and wire-structures. In this work, the effect of the buffer composition, the buffer thickness, and the growth mode on the morphology of self-assembled InAs dots and wires has been also investigated in the InAs/InGaAlAs/InP system. It was found that these growth parameters had the direct influence on the dot-wire transition, and the diagonal space alignment of wires. The atomic processes underlying these growth morphologies will be discussed in detail.

3:45 PM Z7.6
Defect-aided Single Electron and Single Photon Detection in InP/InGaAs and GaAs/AlGaAs Based Quantum Wires and Quantum Point Contacts. Prabhakar Bandaru[1,2], Hideo Kosaka[3,2], Deepak Rao[2], Hans Robinson[2] and Eli Yablonovitch[2]; [1]Materials Science Program, UC, San Diego, La Jolla, California; [2]Electrical Engineering department, UCLA, Los Angeles, California; [3]Fundamental research labs., NEC Corporation, Tsukuba, Japan.

Defects, such as point defects and impurities, play an increasingly important role in nanostructures and devices such as single electron transistors(SETs). The talk will focus on how defect engineering in quantum wires and quantum dots can be used for extremely sensitive ($\sim 10^{-5} e/sqrt Hz$) electron and photon detection. We will report on our experiments in quantum wires and Quantum Point Contacts (QPCs) fabricated in InP/InGaAs and GaAs/AlGaAs heterostructures. Charge trapping by defects in quantum wires is manifested in the occurrence of Random Telegraph Signal (RTS) noise in the Conductance(G)-Voltage(V) spectra. Careful analysis of the RTS noise yielded defect-specific information, such as the presence of a single stray donor atom in a quantum well. In another study, the binding of holes by DX-centers present in (Al,Ga)As was utilized for single photon detection [1, 2]. Potential applications in nano-electronics and quantum information processing will be discussed. 1. H. Kosaka et al., Phys. Rev. B, 65, 201307 (R), 2002. 2. P. Bandaru et al., SPINTECH I, 2001. This work was sponsored by Defense Advanced Research Projects Agency and Army Research Office Nos. MDA972-99-1-0017 and DAAD19-00-1-0172.

4:00 PM Z7.7
Improving the Structural and Optical Properties of 1.3 μm InAs/GaAs Quantum Dots Using InAlAs Layers.
Hui Yun Liu[1], Ian Sellers[2], Mark Hopkinson[1], Colin N. Harrison[1], David J. Mowbray[2] and Maurice S. Skolnick[2]; [1]Department of Electronic & Electrical Engineering, EPSRC National Centre for III-V Technologies, Sheffield, S-Yorkshire, United Kingdom; [2]Department of Physics & Astronomy, University of Sheffield, Sheffield, South Yorkshire, United Kingdom.

Self-organized InAs/GaAs quantum dots (QDs) have gained much interesting due to their unique atomic-like properties and potential device applications. In recent years, the continuing interesting is driven by the extension of emission wavelength of InAs/GaAs QDs to an important telecommunication wavelength of 1.3 μm, and the development of 1.3 μm InAs/GaAs QD laser has progressed rapidly. However, their performance is still limited by gain saturation of the QD ground-state transition, and high temperature stability is compromised by carrier excitation into QD excited states and/or out of the dots. The growth approach of InAs islands directly deposited on InGaAs strained buffer layer (SBL) has been widely used to increase the dot density and hence improve the gain of 1.3 μm QD laser. To extend the InAs QD wavelength to 1.3 μm, an InGaAs strain-reducing layer (SRL) has also been widely used to directly cover InAs QDs. However, the InGaAs SBL and SRL used in these techniques result in a reduced energy barrier and, consequently, an increase of the temperature sensitivity of the laser devices. Furthermore, to improve the optical gain, it is not only necessary to increase the dot density but also to improve their radiative recombination efficiency, particularly at high temperatures. Here, a combination of InAlAs-GaAs strained buffer layer and InAlAs-InGaAs composite strain-reducing layer was presented to tailor increase the dot density and energy barrier of 1.3 μm InAs/GaAs quantum dots. This growth technique exhibits an increment of InAs quantum-dot density from 160 to 280 μm-2 and an improvement of energy separation between the quantum-dot ground and first-excited states from 84 to 93 meV with adjusting the thickness of GaAs in InAlAs-GaAs buffer layer. The experimental relationship between InAs QD density and matrix of InAlAs-GaAs SBL could be understood in term of the increasing additional material from wetting layer into dots and the decreasing repulsive strain field between neighboring islands within substrate. We also investigate the effect of InAlAs layer surrounding InAs quantum dots on optical properties. With increasing (decreasing) InAlAs (InGaAs) thickness in the strain-reducing layer grown above the QDs, the integrated photoluminescence intensity of the QD ground-state transition increases dramatically and the emission wavelength decreases slightly from 1.36 to 1.31 μm. The enhancement of the photoluminescence efficiency is temperature dependent, being much greater above 200 K. A maximum enhancement of 450 is achieved at room temperature. This improvement of the high temperature photoluminescence efficiency should lead to a significant improvement in the characteristics of 1.3-μm InAs/GaAs QD lasers.

4:15 PM Z7.8
Growth and characterization of InAs quantum dots on GaAs (100) emitting at 1.31μm. Vincent Celibert[1,2], Bassem Salem[1], Gerard Guillot[1], Catherine Bru-Chevallier[1], Laurent Grenouillet[2], Philippe Gilet[2] and Alain Million[2]; [1]Laboratoire de Physique de la Matiere, Villeurbanne, France; [2]CEA-DRT-LETI/DOPT, Grenoble, France.

The interest for quantum dots (QDs) remains strong in the domain of telecommunications or quantum cryptography for example. Even if recent achievements made possible to approach on GaAs substrate the1.55μm window of telecommunications, reserved up to now to InP, it remains very important to control the growth of QDs emitting at 1.3μm on GaAs. In this work, we investigate the influence of various parameters on the growth of self-assembled InAs/GaAs QDs and study their optical properties, the ultimate goal being to integrate them in the active zone of vertical cavity surface emitting lasers (VCSELs). The growth was carried out by gas source molecular beam epitaxy (GSMBE) in the Stranski-Krastanov mode by optimizing two significant parameters: samples are grown using a very low deposit rate of InAs increasing the average size of the dots and thus allowing higher wavelength emission. A high speed deposit rate of the GaAs encapsulation layer is chosen in order to rapidly freeze the structure of QDs to avoid any modifications. Structural and optical characterizations are carried out by means of atomic force microscopy (AFM), photoluminescence (PL), and PL excitation (PLE). The mean height, width, length and density of the dots measured from AFM images are 7nm, 40nm, 55nm, and 2x10$\hat{1}$0cm-2, respectively. A good size homogeneity is also observed. The PL properties of QDs measured at 300K show an emission at 1.31μm, with a full width at half maximum around 20meV, which reveals a narrow QD size dispersion. The integrated PL intensity remains very strong at room temperature, as much as 10% of that measured at 8K, indicating an efficient spatial localization of the carriers in the InAs QDs. Four optical transitions are clearly observed in the PL spectrum at 8K under strong excitation density. In order to identify the origin of these optical transitions, PL as function of excitation density has been performed, showing only one optical transition at low excitation, in agreement with a unimodal size distribution. For high excitation density, three excited states are arising due to a state filing phenomenon. These excited levels are also studied by PLE at low temperature as this technique is expected to describe the absorption of the sample weighted by the different recombination paths. The relative importance of absorption and relaxation of the photo-carriers created in the QDs is discussed from the PLE spectra and complementary measurements. Due to a very good reproducibility of the growth, many samples exhibited very close characteristics: this is promising for the fabrication of VCSEL devices containing QDs in their active layer.

4:30 PM Z7.9
Abstract Withdrawn

SESSION Z8: Zinc Oxide
Chairs: Daniel Friedman and Chennupati Jagadish
Thursday Morning, December 4, 2003
Room 208 (Hynes)

8:30 AM Z8.1
Hydrogen Bonding in Zinc Oxide. Norbert H. Nickel[1], K. Brendel[1] and K Fleischer[2]; [1]Hahn-Meitner-Institut, Berlin, Germany; [2]Technical University Berlin, Berlin, Germany.

In the past ZnO has attracted a great deal of interest because of its optical and electrical properties for a variety of applications ranging from UV light emitting diodes to piezoelectric devices. However, a major drawback is the fact that ZnO almost always shows n-type conductivity. Recently, based on first-principles calucations it has been suggested that the observed n-type conductivity is due to H atoms that act as shallow donors [1]. In order to elucidate the role of hydrogen in ZnO single crystal and sputter deposited polycrystalline Zno samples were characterized with Raman backscattering spectroscopy and hydrogen effusion measurements. In state-of-the art nominally undoped ZnO single crystals six local vibrational modes were observed at 2854, 2890, 2918, 2948, 2988, and 3096 cm^{-1}. While the local vibrational modes between 2854 and 2988 cm^{-1} are due to symmetric and antisymmetric stretching modes of C-H_X (X=1, 2, 3) the mode at 3096 cm^{-1} is indicative of the stretching vibration of N-H. An anneal up to 950 °C removes hydrogen from the samples and the local vibrational modes disappear. This establishes that the local vibrational modes are caused by the presence of H in ZnO. H effusion measurements reveal that the H concentrations range from 5.2x10^{16} for single crystal ZnO to 3x10^{21} cm^{-3} for polycrystalline ZnO. From the H effusion spectra the H chemical-potential is determined as a function of the H concentration that can be related to the H density-of-states (DOS) distribution. State-of-the-art single crystal ZnO reveals six peaks in the H-DOS located between 0.59 and 1.4 eV below the energy of the H transport site. With increasing H concentration the amount of hydrogen accommodated with binding energies larger than 1.0 eV increases to about 75%. [1] C. G. Van de Walle, Phys. Rev. Lett. 85, 1012 (2000).

8:45 AM Z8.2
Ion Implantation of ZnO: Opportunities and Challenges.
Sergei O. Kucheyev[1], J. S. Williams[2], C. Jagadish[2], J. Zou[3], C. Evans[1], A. J. Nelson[1] and A. V. Hamza[1]; [1]Lawrence Livermore National Laboratory, Livermore, California; [2]RSPhysSE, Australian National University, Canberra, Australian Capital Territory, Australia; [3]Division of Materials and Centre for Microscopy and

Microanalysis, University of Queensland, Brisbane, Queensland, Australia.

Excellent fundamental material properties as well as recent significant success in the growth of high-quality single crystals make ZnO an ideal candidate for a range of (opto)electronic device applications. However, in addition to desired fundamental properties, the fabrication of ZnO-based (opto)electronic devices obviously requires development of a device processing technology. Indeed, at present, there are significant challenges for processing ZnO including electrical doping. Ion implantation — a powerful device processing tool — can be used for selective-area doping of ZnO. However, ion-beam-produced lattice disorder and its undesirable consequences limit technological applications of ion implantation. In this presentation, we discuss ion-beam-produced structural damage in wurtzite bulk ZnO studied by a combination of Rutherford backscattering/channeling (RBS/C) spectrometry, cross-sectional transmission electron microscopy (XTEM), x-ray photoelectron spectroscopy (XPS), and atomic force microscopy (AFM). In particular, the following aspects of ion-beam processes in ZnO are discussed: (i) the influence of implant conditions on the damage buildup behavior, (ii) strong dynamic annealing and its consequences, (iii) defect types, and (iv) chemical effects due to high concentration of implanted species. Current challenges of ion implantation as a processing tool for ZnO-based devices will be discussed based on our experimental findings. Work at LLNL was performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under Contract No. W-7405-Eng-48.

9:00 AM Z8.3
Properties of Phosphorus-Doped $Zn_{1-x}Mg_xO$ Thin Films.
Young-Woo Heo, Y.W. Kwon, S.J. Park, B.S. Jeong, J. M. Erie, M. Ivill, K. Ip, S. J. Pearton, P. H. Holloway and D. P. Norton; Materials Science and Engineering, University of Florida, Gainesville, Florida.

ZnO is an interesting wide bandgap II-VI semiconductor. Key issues in ZnO electronic and photonic device development are achieving p-type conductivity, as well as fabricating heterostructures for bandgap modulation. In this study, the synthesis and properties of phosphorus-doped $Zn_{1-x}Mg_xO$ thin films will be described. The bandgap of ZnO can be increased to nearly 4.0 eV by making epitaxial (Zn,Mg)O alloys. In this work, epitaxial (Zn,Mg)O thin films were grown by pulsed-laser deposition. Phosphorus doping concentration up to 5 at% have been explored. The transport properties of as-deposited and post-annealed films will be reported, with emphasis on understanding the possible formation of an acceptor state with P substitution on the oxygen site. Annealing temperatures range from 400 $\sim$ 700°C. The behavior of phosphorus-doped $Zn_{1-x}Mg_xO$ (x=0 to 35 %) as a function of Mg content will be presented. Characterization includes Hall measurements for transport, atomic force and scanning electron microscopy for surface morphology, x-ray diffraction for crystallinity, and low-temperature photoluminescence for defect studies.

9:15 AM Z8.4
Preparation and characterization of N-doped or N-Al-N codoped p-type ZnO films. Jingyun Huang, Zhizhen Ye, Guodong Yuan, Jianguo Lu and Binghui Zhao; State Key Laboratory of Silicon Materials, Zhejiang University, Hangzhou,310027, China.

It is necessary but difficult to prepared p-type ZnO films in order to fabricate ZnO-based optical devices. In this paper, the c-oriented and real-time nitrogen-doped or N-Al-N codoped p-type ZnO films on silicon or sapphire substrates were prepared by magnetron sputtering using ammonia as dopant source gas. The properties of the ZnO: N films were investigated with X-ray diffraction (XRD), spreading resistivity profile (SRP), Fourier transform infrared spectroscopy and Hall-effect measurements. Hall measurements showed that the carrier density of the p-type ZnO films on sapphire varied from 1.14*10sup(12) to 8.02*10sup(18)cm sup(-3) while the Hall mobility varied from 66.4 to 0.802 cm sup(2)/Vs at room temperature. A model of "chemical passivation aid doping" is introduced to explain the doping mechanism. The N dopant concentration is remarkably enhanced because of the N-H atom pair. The nitrogen acceptor is effectively activated when the N-H bond is dissociated. The dissociated hydrogen atoms interact with oxygen vacancies and passivate the dangling bonds. We expect this result to facilitate the fabrication of the steady p-ZnO films suitable for light-emitting diodes.

9:30 AM Z8.5
Effect of oxygen radical irradiation and cation doping on structures and electric properties of zinc oxide films deposibed by PLD technique. Ryoken Haruki[2,1], Naoki Ohashi[1], Ohgaki Takeshi[1], Isao Sakaguchi[1], Takashi Sekiguchi[1], Yutaka Adachi[1], Tadashi Takenaka[2] and Hajime Haneda[1]; [1]Electroceramics Group, National Institute for Materials Science, Tsukuba, Ibaraki, Japan; [2]Department of Electrical Engineering, Tokyo University of Science, Noda, Chiba, Japan.

Zinc oxide (ZnO) is one of the well-know wide-gap semiconductor for transparent electrode applications. In order to make it functional devices, it is necessary to control its band-gap, Fermi level and conductivity. The achievements in band-gap engineering of ZnO will be a key for opening a door introduce us to a world of transparent switching devices, such as transparent field effect transistors and so on. In this study, we investigated relationships between amount of dopant, lattice parameters, electric conductivity and optical properties of ZnO thin films in order to obtain basic knowledge for fabrication of transparent electronics using ZnO and its related alloys. The films were grown by pulsed laser deposition (PLD) method using a PLD apparatus equipped with an r. f. plasma gun for oxygen radical irradiation. All the films were deposited under pressure of 10-5 torr under O_2 gas leak of oxygen radical irradiation. Substrate temperature was set to 400-700 °C and the forth harmonic generation of pulsed Nd:YAG laser was used for abrasion of ceramic targets. The composition of the films were (Zn, Al)O_x or (Zn, Al, Mg)O_x. The grown films were characterized by measuring x-ray diffraction patterns, atomic force microscope images, photo- and cathodoluminescence spectra, electric conductivity, and Hall effect. Significant decrease of electric conductivity was found in the films irradiated by oxygen radical during film deposition. It was also found that lattice parameters of ZnO varied by radical irradiation. From the results of film deposition and characterizations, we will discuss about degree of nonequilibrium in ZnO films and charge compensation and defects formation in the ZnO based transparent conductors under nonequilibrium conditions. We will also mention about ZnO modulation doping structures.

9:45 AM Z8.6
Characterization of Transition Metal Doped ZnO.
Matthew H Kane[1], Zhe Chuan Feng[2], Ian T Ferguson[2], Varatharajan Rengarajan[3], Jeffrey Nause[3], Brent Wagner[4] and Christopher Summers[1,4]; [1]Materials Science and Engineering, Georgia Institute of Technology, Atlanta, Georgia; [2]Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, Georgia; [3]Cermet, Inc., Atlanta, Georgia; [4]Georgia Tech Research Institute, Georgia Institute of Technology, Atlanta, Georgia.

ZnO has a wide and direct band gap of 3.36 eV at room temperature and an exciton binding energy of 60 meV which is higher than that of GaN of 28 meV. It is a promising materials for blue-UV light emitting devices and also a possible candidate as substrate for the growth of III-nitrides. ZnO doped with transition metal elements has attracted interest for the application in the field of spintronics. Theoretical predictions and some experimental results have indicated that it is a promising room temperature ferromagnetic semiconductor. There is, however, more work needed to elucidate the mechanism of ferromagnetism in these materials and develop them for device applications. Here, we report on the material properties of ZnO doped with Mn, Co, and Fe grown by a patented technique. X-ray diffraction measurements show that transition metals can be incorporated on Zn sites. An increase in lattice parameter is apparent with increasing doping level. Phase purity is incomplete, possibly due to non-stoichiometry in the growth process. UV-visible transmission and reflectance measurements have been performed. Absorption bands in the visible regime are distinctive to the individual dopants. A large shift in the band edge has been observed from these Mn/Co/Fe-doped ZnO crystals in comparison with un-doped ZnO, with information of the impurity levels of these dopants obtained. ZnO provides also a suitable platform for the incorporation of transition metal elements through equilibrium growth processes, although further work is required in order to use these materials for spintronic applications.

10:30 AM Z8.7
Improvement in Device Response of homo and heteroepitaxially grown MgxZn1-xO ultra violet light detector. Shiva S Hullavarad[1], Ichiro Takeuchi[1], Vishwas Kulkarni[1], T Venkatesan[1], R D Vispute[2,1] and S N Yedave[2,1]; [1]Center for Superconductivity Research, University of Maryland, College Park, Maryland; [2]Blue Wave Semiconductors, Inc, Columbia, Maryland.

MgZnO is a novel oxide based UV sensitive material. The band gap of MgxZn1-xO can be tuned by varying the composition of Mg to achieve band gaps corresponding to UV-A, UV-B and UV-C regions of UV spectrum. This material is of significant importance for various applications in flame sensors, UV index monitors and missile plume detection. The interesting property that makes this material unique is its existence in multiple phases for different Mg compositions. This allows picking up the desired Mg composition corresponding to suitable UV sensitive window and growing on lattice matched substrate. In this work we report homoepitaxial growth of hexagonal MgxZn1-xO for x<0.3 and cubic for x>0.45 composition on lattice matched substrates. The substrates are chosen in such a way that

they match the lattice structure of MgxZn1-xO for hexagonal and cubic phases. The films are characterized by X-ray diffraction, and Rutherford back scattering techniques for crystalline quality and stoichiometry respectively. The epitaxial nature of film is monitored by RBS-channeling studies. Metal-Semiconductor-Metal structures are fabricated on the hexagonal and cubic phase MgxZn1-xO grown on lattice matched substrates. The photo response of the device is studied and compared to devices formed on sapphire substrate. The enhancement in device properties is attributed to the reduction in strain at the interface of MgxZn1-xO with the lattice matched substrate.

10:45 AM Z8.8
Improved Epitaxy in the Growth of Low-temperature Pulsed Laser Deposited (PLD) Zinc Oxide on C-axis Sapphire Using a Higher Temperature Buffer Layer. Hugh Porter[1], Jagdish Narayan[1], Ailing Cai[2] and John Muth[2]; [1]Materials Science and Engineering, North Carolina State University, Raleigh, North Carolina; [2]Electrical and Computer Engineering, North Carolina State University, Raleigh, North Carolina.

Epitaxial zinc oxide is attracting increased attention because of its high potential for wide band gap light emitters and photodiodes in the blue and ultraviolet portion of the spectrum. However, a variety of problems associated with preparing p-type zinc oxide must be solved before these devices can be fabricated. Unintentional oxygen vacancies are blamed for natural n-type behavior, and it has been observed that zinc oxide grown at lower temperatures tends to have less oxygen vacancies. One strategy for filling these oxygen vacancies is to dope with a small amount of ZnTe, so that the tellurium atoms can fill oxygen sites. But again, the need to grow at lower temperatures is still an issue as ZnTe will not incorporate into the films at temperatures above 500^o C. The best epitaxial films of ZnO on c-axis sapphire have been shown to grow at around 700^o C. We demonstrate a method of growing high quality ZnO:Te thin films at lower temperatures (~400^o C) on c-axis sapphire by first growing a 15 nm high quality template of ZnO at 700^o C. Transmission electron microscopy (TEM) studies of the films grown without this buffer layer show many low angle grain-boundaries, and a broader (0002) peak in high-resolution x-ray diffraction (HRXRD) rocking curve. The samples grown with the buffer layer, however, show much better crystallinity, with HRXRD rocking curve full-width-at-half-maximum (FWHM) values around 1500 arcseconds.

11:00 AM Z8.9
Influence of high-temperature annealing on MOVPE grown ZnO using tertiary-butanol as O-precursor. Frank Bertram, Daniel Forster, Juergen Christen, Armin Dadgar, Anette Diez, Andre Krtschil, Nikolay Oleynik and Alois Krost; Institute of Experimental Physics, Otto-von-Guericke-University Magdeburg, Magdeburg, Germany.

ZnO layers (~0.4 μm thick) were grown by MOVPE at 450°C with tertiary-butanol on GaN/Si templates. The layers are subsequently heated in-situ up to 900°C under N_2O atmosphere. A change in the surface morphology of the sample with annealing time is observed in AFM and SE images. The annealing process starts with an initial roughening. The AFM rms roughness (10x10 μm^2) increases from ~30 nm to 40 nm immediately after heat up. The roughness then drastically decreases to rms values of 6.7 nm after ~2-4 min annealing time followed by a slow minor increase for further annealing. The laterally integrated spectrum measured by cathodoluminescence (CL) consists of two spectral regions: the excitonic near band edge emission (~370 nm) and a broad defect band at about 520 nm. The near band edge emission is dominated by acceptor bound exciton related (I8) luminescence. In addition, the free exciton X and several donor bound exciton lines I0-I3 are visible in the spectrum. We observe a narrowing of the near band edge lines from >9 meV to 4.5 meV with increasing annealing time. The free exciton and the donor bound lines disappear. Even for short annealing times, i.e. 15 s, the intensity of the defect band reduces drastically by more than an order of magnitude. Again, a further increase of the annealing time leads to a slow increase of the defect band intensity. After the initial jump at the beginning of the annealing, the ratio of near band edge luminescence intensity to the defect band intensity decreases monotonically with annealing time. The dramatic improvement of homogeneity of the ZnO films with annealing is directly visible in panchromatic and monochromatic CL images.

11:15 AM Z8.10
Optical properties of bulk and epitaxial ZnO. Zhe Chuan Feng[1], Shanthi Ganesan[2], D. Mehta[1], Matthew H. Kane[3], Ian Ferguson[1], Jeff Nause[2], Brent Wagner[4] and C. Summers[3,4]; [1]Electrical & Computer Engineering, Georgia Institute of Technology, Atlanta, Georgia; [2]Cermet, Inc., Atlanta, Georgia; [3]Materials Science & Engineering, Cermet, Inc., Atlanta, Georgia; [4]Georgia Tech Research Institute, Georgia Institute of Technology, Atlanta, Georgia.

II-VI compound ZnO is currently attracting more interests in the applications of optolectronics, microelectronics, and spintronics because of its unique properties, wide and direct band gap, large exciton binding energy, super chemical stability, ferroelectrics and ferromagnetics. High quality bulk ZnO crystals and metalorganic chemical vapour deposition (MOCVD) grown ZnO thin films on Si and sapphire substrates have been produced at Cermet. In this study, optical properties of these bulk and epitaxial ZnO materials are investigated, by way of various optical techniques. Raman scattering for measured samples showed a narrow and strong mode at 438 1/cm which is the ZnO E2 mode characteristic of the ZnO crystallinity. The line shape of the E2 mode has been analysed via the spatial correlation model and its variation with the doping elements and levels is found. A broad band near 1150 1/cm appeared. This is the 2LO (two-longitudinal optical phonon) mode due to the coupling between LO phonons and free carriers, characteristic of dopings. Fourier infrared (FTIR) reflectance was measured and analysed by the theoretical oscillation model leading to a non-destructive determination of free-carrier concentration. Photoluminescence (PL) for un-doped ZnO exhibited a strong and narrow band due to the band edge emissions. UV-visible transmission data revealed the variation of optical gaps with different element dopings in ZnO, covering a wide range of 380-600 nm, and a blue shift of the optical gap from the ZnO on sapphire in comparison with the undoped bulk ZnO, indicating a compressive stress in ZnO layer epitaxied on sapphire substrate. Scanning ellipsometry (SE) data and analyses leaded to the determination of the refraction index n and distinguish coefficient k as well as their variations with doping elements and levels. The thickness and optical properties of ZnO films grown on Si and sapphire substrate by MOCVD are also determined.

11:30 AM Z8.11
Deposition and Characteristics of Ternary Zn1-xCdxO Crystal Films. Zhizhen Ye, Dewei Ma, Jingyun Huang, Binghui Zhao and Liping Zhu; State Key Laboratory of Silicon Materials, Zhejiang University, Hangzhou, 310027, China.

Zn1-xCdxO ($0 < x < 1.0$) crystal thin films were deposited on silicon, glass and sapphire substrates by the dc reactive magnetron sputtering technique. X-ray diffraction measurement indicates for the samples with $x<0.6$, the Zn1-xCdxO films are of completely (002)-preferred orientations, i.e., the wurtzite-type structure of ZnO can be stabilized up to nominal Cd content x~0.6 without cubic CdO phase separation. The lattice parameter c of Zn1-xCdxO increases almost linearly from 5.229 A; (x=0) to 5.247 A; (x=0.6), indicating that Cd substitution takes place on the Zn lattice sites. TEM measurements show that for the (002)-oriented films the grains are columnar structures with the c-axes perpendicular to the substrates. XPS measurements also show that the Zn and Cd exist only in the oxidized states, no evidence of metallic Zn or Cd was observed. Transmittance measurements show that the optical band-gaps of the Zn1-xCdxO ($0 < x < 1.0$) films are in the range of 3.28~2.40 eV. Photoluminescence spectra of the Zn1-xCdxO thin films measured at 12 K display a substantial red shift (~0.3 eV) in the near-band-edges emission of ZnO: from 3.30 eV of ZnO to 3.00 eV of Zn0.4Cd0.6O. The direct modulation of bandgap caused by Zn/Cd substitution is responsible for the red shift effect in near-band-edge emission of ZnO. By post-annealing treatments under O2 ambient, the crystal quality of the Zn1-xCdxO ($0 < x < 1.0$) films improves much.

11:45 AM Z8.12
Shallow bound exciton complexes in ZnO. Axel Hoffmann[1], Martin Strassburg[1], Anna Rodina[1], Matthias Dworzak[1], Ute Haboeck[1], Helder R. Alves[2], Arndt Zeuner[2], Detlev M. Hofmann[2], Bruno K. Meyer[2], Olaf Gelhausen[3] and Matthew R. Phillips[3]; [1]Inst. of Solid State Physics, TU Berlin, Berlin, Berlin, Germany; [2]I. Physics Institute, Justus-Liebig-University Giessen, Giessen, Germany; [3]Microstructural Analysis Unit, University of Technology, Sidney, New South Wales, Australia.

Magnetic field dependent optical absorption and photoluminescence (PL) experiments were performed to study shallow bound exciton complexes in Na-, N-, Ga- and In- doped and nominally undoped ZnO. These data were interpreted using theoretical modeling calculations of the ordering of the valence bands, Zeeman splitting, selection rules for optical transitions and thermalization behavior for each of the investigated specimens. Both the angular-dependent magneto-PL results and the theoretical calculations indicate that the top of the valence band in ZnO possesses the $\Gamma 7$ symmetry. The sign and the value of the effective g factor of the holes involved in all bound exciton transitions were determined by analyzing the polarization properties and fitting the angular dependence of the transition energies. The magneto-optical investigations of the In- and Ga- diffusion doped ZnO, particularly the Zeeman splitting in combination with the thermalization properties, provide strong evidence that the enumerated PL emission lines up to I10 at 3.3531

eV, stem from donor-bound excitons. The donor complexes involved in I4 at 3.3630 eV, I8 at 3.3599 eV and I9 at 3.3567 eV have been assigned to be Hydrogen, Gallium and Indium, respectively. However, it was not possible to ascertain the chemical origin for all of the observed shallow exciton lines. A new line at 3.3562 eV was detected in the transmission spectrum of the N-doped ZnO specimen, and its thermalization behavior in a magnetic field suggests it related to an acceptor-bound exciton. Optical transmission experiments on spectrally sharp absorption lines between 3.2941eV and 3.3329eV facilitated a clear distinction between deeply bound excitons and the two-electron satellites (TES) of shallow donor-bound excitons. The observed Zeeman splitting and thermalization behavior excludes an acceptor-bound exciton complex.

SESSION Z9: Spintronics and Quantum Structures
Chairs: F. Danie Auret and Irina Buyanova
Thursday Afternoon, December 4, 2003
Room 208 (Hynes)

1:30 PM *Z9.1
Spin-dependent optical processes in II-VI diluted magnetic semiconductor nanostructures. Yasuo Oka, Institute of Multidisciplinary Research for Advanced Materials, Tohoku University, Sendai, Japan.

Diluted magnetic semiconductors (DMSs) are compound semiconductors, which involve magnetic ions in the cation sites. The DMSs show marked spin-dependent phenomena due to the s (p)-d exchange interaction of band-electrons (-holes) with the involved magnetic ions. We have fabricated nanometer scale structures by II-VI DMS materials, such as quantum dots (QDs), quantum wires (QWRs) and quantum wells (QWs), by using molecular beam epitaxy and electron-beam lithography. Magneto-optical properties and exciton spin dynamics have been studied by time-resolved photoluminescence (PL) and pump-probe absorption spectroscopies with using femtosecond mode-locked pulse lasers. Fabricated QDs, QWRs and QWs of DMSs display low-dimensional excitonic properties and enhanced magneto-optical effects induced by the exchange interaction between electrons and magnetic ions in the quantum-confined nanostructures. The luminescence from the Cd0.97Mn0.03Se QDs grown by the self-organization on a ZnSe substrate layer shows the confined exciton energy due to the dot size of 4 - 6 nm and also shows marked increase of the exciton lifetime and the luminescence intensity with increasing the magnetic field. The increases of the lifetime and luminescence intensity are affected by the suppression of the Auger energy transfer from the exciton to the Mn ions by the magnetic field. The QDs of Zn0.69Cd0.23Mn0.08Se fabricated by the electron beam lithography exhibit narrow exciton PL spectrum due to the uniform shape of the QDs. The exciton luminescence from the QWRs of Cd0.92Mn0.08Se and Zn0.69Cd0.23Mn0.08Se is influenced by the one-dimensional confinement effect for the exciton energy and the luminescence is linearly polarized parallel to the wire direction. The transient PL from the ZnTe/Zn0.97Mn0.03Te QWs displays the magnetic-field induced level crossing in the exciton spin states of the nonmagnetic and magnetic layers and the spatial spin separation for the excitons. Cd0.95Mn0.05Te-CdTe double QWs show the injection dynamics of the spin-polarized excitons from the magnetic QW to the nonmagnetic QW. Ultrafast dynamical processes of exciton spins in DMS QWs in magnetic field are investigated by using the transient pump-probe spectroscopy. With an intense optical pumping at low temperatures, the transient absorption displays the band gap renormalization by the densely created electron-hole plasma, the creation process of excitons, and the excitonic magnetic polaron formation in the time region of 0.4 - 100 ps. The observed spin-dependent optical processes in the nanostructure DMSs show possibilities for the future spin electronics. 1) Y. Oka, K. Kayanuma, S. Shirotori, A. Murayama, I. Souma, and Z. H. Chen, J. Luminescence 100, 175 (2002). 2) K. Kayanuma, E. Shirado, M.C. Debnath, Y. Oka et al., J. Appl. Phys. 89, 7278 (2001). 3) S. Shirotori, K. Kayanuma, T. Tomita, Z. H. Chen, A. Murayama, Y. Oka et al., J. Superconductivity 16, 457 (2003).

2:00 PM Z9.2
Efficiency Of Optical Spin Injection In Znmnse/Cdznse Quantum Structures. Irina A Buyanova[1], Weimin M Chen[1], K Kayanuma[2], Z H Chen[2], A Murayama[2], Y Oka[2], A A Toropov[3], S V Sorokin[3], S V Ivanov[3] and P S Kop'ev[3]; [1]Department of Physics and Measurement Technology, Linkoping University, Linkoping, Sweden; [2]Institute of Multidisciplinary Research for Advanced Materials, Tohoku University, Sendai, Japan; [3]A.F. Ioffe Physico-Technical Institute, St. Petersburg, Russian Federation.

Efficient spin injection across a semiconductor heterointerface is one of the key issues in determining the success of future spintronic devices, and has therefore received great research interest in recent years. Though the efficiency of electrical spin injection has been demonstrated to be higher, the efficiency of optical spin injection is still rather limited (i.e. typically less than 30%). The exact mechanism for the reduced optical spin injection efficiency is up to now unknown, as many physical processes are involved during the spin injection. The aim of this work is to carry out an in-depth investigation of physical processes limiting efficiency of optical spin injection from the ZnMnSe-based diluted magnetic semiconductors (DMS) to an adjacent nonmagnetic ZnCdSe quantum well (QW) as a spin detector. Both cw- and time-resolved photoluminescence (PL) spectroscopies with tunable laser excitation were employed. By selective excitation of only the lowest lying spin state of the DMS exciton in an applied magnetic field, a complete spin polarization within the DMS can be ensured and its role in spin loss can therefore be excluded. The limited spin injection efficiency of about 30% observed in the cw PL studies is therefore caused by spin loss across the heterointerfaces and during the energy relaxation within the QW. From the time-resolved PL studies it is shown that the main portion of the QW PL exhibits extremely fast spin depolarization (within tens of ps) accompanying energy relaxation of hot excitons and hot carriers within the QW, providing explanation for the observed limited efficiency of optical spin injection.

2:15 PM Z9.3
GaMnN - Material for Spintronics grown by MOCVD. David Mistele and Joseph Salzman; Microelectronics Research Center, Dept of Electrical Engineering, Technion - Israel Institute of Technology, Haifa, Israel.

The idea of using the spin property in semiconductors created the emerging field of spintronics. The control of spin is correlated to the magnetic properties of the semiconductor and it is theoretically predicted and experimentally proven that Nitride semiconducting compounds with incorporated transition metals may form ferromagnetic layers with Curie-temperatures above RT. First attempts towards this goal were achieved successfully mainly by MBE-techniques [1], implantation [2], or other more exotic growth techniques [3]. We approach the growth of GaMnN as well as GaInMnN and AlMnN by MOCVD. We carefully have chosen the MO-source as MCp2Mn, which is also used for the successful growth of GaMnAs [4]. Our growth regimes include investigations on the effect of substrate temperatures, different molar flows, and different nitrogen sources. Incorporation of Mn is investigated chemically by EDX, AES, and SIMS. Optical characterization show distinct Mn-related peaks in the red spectra around 700nm. Next to the MOCVD growth, implantation of Mn into GaN was performed at 250keV and GaMnN of both techniques were compared intensively. Magnetic measurements are underway by magnetic photoluminescence, by the anomalous Hall-effect at low temperatures, as well as susceptibility measurements by VSM (Vibrating Sample Magnetometer) and the results will be presented. [1] S. Sonoda, S. Shimizu, T. Sasaki, Y. Yamamoto, H. Hori; J. Cryst. Growth 237-239, 1358 (2002). [2] S. J. Pearton, C. R. Abernathy, M. E. Overberg, G. T. Thaler, D. P. Norton, N. Theodoropoulou, A. F. Hebard, Y. D. Park, F. Ren, J. Kim, L. A. Boatner; J. Appl. Phys. 93 (1), 1 (2003). [3] M. Zajac, J. Gosk, E. Grzanka, M. Kaminska, A. Twardowski, B. Strojek, T. Szyszko, S. Podsiado, J. Appl. Phys. 93 (8), 4715 (2003). [4] Th. Hartmann; M. Lampalzer, P.J. Klar, W. Stolz, W. Heimbrodt, H.-A. Krug von Nidda, A. Loidl, L. Svistov; Physica E 13, 572 (2002).

2:30 PM Z9.4
Microstructure and Interfaces of $CdCr_2Se_4$ on AlGaAs and ZnSe. George Spanos[1], Ramasis Goswami[2], George Kioseoglou[1], Aubrey Hanbicki[1] and Berry Jonker[1]; [1]Naval Research Laboratory, Washington DC, District of Columbia; [2]Geo-Centers, Fort Washington, Maryland.

The discovery of ferromagnetism in semiconductors has attracted considerable attention due to the potential for developing magneto-electronic devices using both the electron spin and charge. It has been shown that the spin polarized electrons from ferromagnetic semiconductors (FMSs) can be injected into light emitting diodes (LEDs) in order to track the spin polarization and observed that the spin injection efficiency depends largely on the microstructure as well as the interface between the FMS and the semiconductor. Recent work has demonstrated epitaxial growth of n-type $CdCr_2Se_4$ on GaP and GaAs [1]. $CdCr_2Se_4$ is a ferromagnetic semiconductor (FMS) with Curie temperature 130K. The purpose of the present work is to elucidate the microstructural evolution of the $CdCr_2Se_4$ films grown by molecular beam epitaxy (MBE) on AlGaAs/GaAs LEDs at different temperatures, and to characterize the defects and heterointerface using high-resolution transmission electron microscopy (HRTEM). Films of $CdCr_2Se_4$ were also deposited on ZnSe/AlGaAs/GaAs-LED. Nanoparticles of CdSe are observed to be formed along the (111) habit plane of $CdCr_2Se_4$ in all cases. HRTEM reveals that the interface between $CdCr_2Se_4$ and AlGaAs has a disordered layer. We also discuss here the role of the microstructure

and interfaces in improving the spin injection efficiency. This work was supported by the DARPA SpinS Program and ONR [1] Y.D. Park et al., Appl. Phys. Lett., 81, 1472 (2002)

2:45 PM Z9.5
Mixing Rocksalt and Wurtzite Structure Binary Nitrides to Form Novel Ternary Alloys: ScGaN and MnGaN.
Costel Constantin, Hamad Al-Brithen and Arthur Reed Smith; Physics and Astronomy, Ohio University, Athens, Ohio.

Ternary nitride semiconductors are currently of widespread interest for their potential properties ranging from electronic to magnetic. However, since many alloys of interest require the combination of materials having disparate equilibrium binary crystal structures, for example the combination of rock-salt MnN with wurtzite GaN to form $Mn_xGa_{1-x}N$, it is very important to explore the growth and structure of these materials. Of fundamental interest is how an atom preferring octohedral bonding can substitute for one preferring tetrahedral bonding, and vise-a-versa. We currently are investigating several alloys of this case: 1) MnGaN, with potential spintronic applications, and 2) ScGaN, with potential electronic applications. ScN has a well-known rock-salt structure but is also expected to have a metastable wurtzite phase exhibiting a band gap smaller than that of wurtzite GaN.[1] This suggests the possibility of forming wurtzite ScGaN alloys with varying band gap. Thus we have investigated the growth of crystalline $Sc_xGa_{1-x}N$ alloys on sapphire(0001) substrates with x spanning the range from 0-100%. The films are grown using radio frequency molecular beam epitaxy at a substrate temperature of 650°C. The flux ratio of Sc/Ga and the total metal flux are carefully controlled, and the films are monitored in-situ using reflection high energy electron diffraction (RHEED). For ScGaN, we observe three different regimes of growth: 1) a wurtzite regime for x = 0-30%, 2) a rocksalt regime for x = 55-100%, and 3) a mixed regime for 30% < x < 55%. In the wurtzite regime, x-ray diffraction (XRD) does not show any second phase peaks, but it also shows no significant shift in the third order $Sc_xGa_{1-x}N$ peak, similar to our findings in the case of MnGaN.[2] However, the RHEED streak spacing shows a variation with Sc concentration tending toward larger values of lattice spacing a with increasing Sc fraction, suggesting that the strain is in the c-plane rather than between c-planes. Correspondingly, optical absorption finds the bandgap decreasing with increasing Sc fraction. Linear extrapolations of the bandgap and lattice constant to x=100% find effective values for wurtzite ScN in reasonably good agreement with a recent theoretical paper.[1] In the rocksalt regime, the optical absorption similarly finds the bandgap decreasing with increasing Sc fraction, reaching 2.15 eV (bandgap of rocksalt ScN)[3] at x=100%. Linear extrapolations of this data to x=0% results in an effective bandgap for rocksalt GaN. Where possible, comparisons will be made to the case of MnGaN. 1. N. Takeuchi, Phys. Rev. B **65**, 045204 (2002). 2. M. Haider *etal.*, J. Appl. Phys. **93**(**9**), 5274 (2003). 3. A. R. Smith *etal.*, J. Appl. Phys. **90**, 1809 (2001).

3:30 PM *Z9.6
Wide Bandgap Semiconductors for Semiconductor Spintronics. Stephen John Pearton[1], Cammy R. Abernathy[1], Gerry Thaler[1], Rachel Frazier[1], David Norton[1], Josh Kelly[2], Ryan Rairigh[2], Art Hebard[2], Y.Dan Park[3] and John M. Zavada[4]; [1]Materials, Univ.Florida, Gainesville, Florida; [2]Physics, University of Florida, Gainesville, Florida; [3]Center for Stongly Correlated Materials Research, Seoul National University, Seoul, South Korea; [4]US Army Research Office, Research Triangle Park, North Carolina.

The relatively new field of semiconductor spintronics seeks to exploit the spin of charge carriers in new generations of transistos,lasers and IC's.The ability to control spin injection,transport and detection leads to the potential for new classes of ultra-low power,high speed logic ,memory and photonic devices.The utility of such devices depends on the availability of materials with practical magnetic ordering temperatures.In this talk we will summarize recent progress in dilute magnetic semiconductors such as (Ga,Mn)N,(Ga,Mn)P and(Zn,Mn)O exhibiting room temperature ferromagnetism,the origins of the magentism and its potential applications in novel devices such as spin-polarized light emitters and spin field effect transistors

4:00 PM Z9.7
Optical Investigation of CdSe/Zn(Be)Se Quantum Dot Structures: Size, Cd Composition and Phonons. Yi Gu[1], Igor L Kuskovsky[1], Jennifer Fung[1], Rich Robinson[1], Irving P Herman[1], Gertrude N Neumark[1], Xuecong Zhou[2], Shiping Guo[2] and Maria C Tamargo[2]; [1]Department of Applied Physics and Applied mathematics, Columbia University, New York, New York; [2]Department of Chemistry, City College of CUNY, New York, New York.

Self-assembled quantum dot (QD) systems have been of great interest due to their unique optical properties. CdSe/ZnSe nano-structures are among the most studied systems because of their promising applications in opto-electronic devices. For device applications, it is crucial to determine properties (such as size and Cd composition [Cd]) of optically active QDs. Here, we investigate optical properties of $CdSe/Zn_{0.97}Be_{0.03}Se$ and CdSe/ZnSe QDs, grown under similar conditions, using photoluminescence (PL), PLExcitation (PLE) and Raman scattering spectroscopy. We complement these studies by calculating PL transition energies using a spherical QD model with finite barriers. The calculation shows that the difference in PL between these two samples can only be accounted for by the formation of QDs with smaller size and/or lower [Cd] in the $CdSe/Zn_{0.97}Be_{0.03}Se$ system. Furthermore, we have observed LO and surface phonons of QDs for $CdSe/Zn_{0.97}Be_{0.03}Se$ from both PLE and Raman scattering spectroscopy; however, no phonon peak has been observed from PLE for our CdSe/ZnSe sample, suggesting weaker phonon-exciton coupling in this system. Additionally, the QDs LO phonon energy is calculated including strain and size effects. Combining these studies, we are able to estimate size (diameter d) and [Cd] of optically active QDs in $CdSe/Zn_{0.97}Be_{0.03}Se$. We shall show that for our $CdSe/Zn_{0.97}Be_{0.03}Se$ nanostructures, the PL is dominated by QDs with 5.1< d< 8nm and 47%< [Cd]< 54%.

4:15 PM Z9.8
PbSe Nanorod Liquid Crystals: Bulk Ordering and Polarized Infrared Emission. Richard D. Schaller, Sohee Jeong, Victor I. Klimov and Jennifer A. Hollingsworth; Chemistry Division, Los Alamos National Lab, Los Alamos, New Mexico.

Quantum dots of PbSe have been shown to exhibit band edge emission that is tunable in the near-infrared with very high emission quantum yields (~80%) making the materials attractive for technologies ranging from telecommunications to biological labeling. We have recently developed a synthetic route to elongated PbSe nanocrystals (NCs) (i.e. nanorods) and show that they form birefringent liquid crystalline domains in concentrated solutions. We demonstrate that these nanorod domains can be aligned using shear flow techniques. We have also constructed an electrode/NC/electrode sandwich device and demonstrate that we can control liquid crystal domain orientation using applied electric fields. Next, a shear flow aligned sample of PbSe liquid crystals is demonstrated to emit photoluminescence that is polarized due to the combined characteristics of polarized emission from individual nanorods and the bulk ordering of the material. Polarized emission is then measured in the near-infrared at a primary telecommunications wavelength (1550 nm) from a bulk sample of aligned PbSe liquid crystalline domains. Experiments performed with concentrated solutions of spherical PbSe quantum dots that have been prepared identically to the nanorod samples do not exhibit polarized emission. Electro-optic devices incorporating PbSe nanorod liquid crystals will allow one to control the polarization of photoluminescence signals with electric fields. Such devices could act as infrared optical switches and modulators.

4:30 PM Z9.9
Modification of MBE-Grown ZnO Nanorods with Magnesium and Cobalt - Effects on Microstructure and Properties. Karin Pruessner[1], Young-Woo Heo[1], Kelly Ip[1], Michael J. Kaufman[1], Matthew F. Chisholm[2], David P. Norton[1] and Stephen J. Pearton[1]; [1]Department of Materials Science and Engineering, University of Florida, Gainesville, Florida; [2]Solid State Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee.

ZnO is an n-type, direct bandgap oxide semiconductor. It's photonic, electronic and chemical sensing properties make it an interesting material for functional nano-devices. The ability to grow defined nanostructures, manipulate them and tailor their properties is critical for these applications. The bandgap of ZnO is Eg=3.35 eV, the n-type behavior is due to Zn interstitials or hydrogen. Intentional doping can be used to modify the properties. The bandgap of ZnO can be tailored by addition of Mg or Cd. Transition-metal doped ZnO also exhibits interesting magnetic properties for use in spintronic devices. Curie temperatures above 300 K have been reported in the literature for Mn- and Co-doped ZnO. The origin of the observed ferromagnetism is not yet clear though. In our experiment, ZnO nanorods were grown assisted by Ag catalyst particles on silicon wafers in a MBE system. Growth temperatures were typically in the range between 300 and 600°C. This process permits site-specific nucleation and growth of nanorods. Compositional modification of the rods was accomplished (i) by simultaneous or sequential use of a Zn and a Mg source in the MBE chamber, and (ii) by ion-implantation of Co-atoms into the nano-rods. Nanorods were implanted with 250 keV Co+ ions (dose: $5x10^{16}$ cm^{-2}) producing surface concentrations of about 3-5 at.-%. Implantation was performed at ~350°C to avoid amorphization and specimens were subsequently annealed at 700°C. The microstructure of these modified nanorods was characterized using X-ray diffraction and scanning and transmission electron microscopy techniques. The optical and magnetic properties were characterized. The (Zn,Mg)O nanorods were found to be typically 15-40 nm in diameter and more than 1 μm long. They exhibit a single-crystalline core of hexagonal $(Zn_{1-x}Mg_x)O$ surrounded by MgO in the cubic rocksalt structure.

Photoluminescence studies showed a shift of the band-edge photoluminescence due to the Mg-doping. The Co-doped nanorods showed ferromagnetic behavior at low temperatures. Unimplanted ZnO shows paramagnetic behavior. X-ray measurements indicate the presence of hexagonal Co in the ZnO matrix, which could account for the magnetic behavior. Co incorporation into the ZnO lattice could also contribute to the effect. The growth mechanism and structural development of the nanorods and their effect on the observed properties will be discussed.