SYMPOSIUM I

GaN and Related Alloys

November 26 – 30, 2001

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* Invited paper

SESSION I1: MOLECULAR BEAM EPITAXY AND GROWTH KINETICS

Chair: Theodore D. Moustakas
Monday Morning, November 26, 2001
Room 302 (Hynes)

8:30 AM *I1.1
AlGaN/GaN HETEROJUNCTION DEVICES GROWN BY IMPROVED RF-PLASMA MOLECULAR BEAM EPITAXY. Katsumi Kishino, Akihiko Kikuchi Sophia University, Tokyo, JAPAN.

InGaN/AlGaN semiconductor lasers are successfully fabricated by metal organic chemical vapor deposition (MOCVD). In the fabrication of AlGaN/GaN quantum heterojunction devices, such as inter-subband transition (ISBT), resonant tunneling diodes (RTD) and HEMT, however, it is essential to manage the hetero-boundary sharpness and the layer thickness in one mono-layer (ML) order. In this respect, the rf-plasma molecular beam epitaxy (RF-MBE) may have an advantage over MOCVD. In this talk, we will discuss AlN/GaN heterojunction structures with RTD, ISBT and HEMT schemes fabricated by improved RF-MBE technology. As a conduction band offset in AlN/GaN hetero-junction is very large to be 2eV, it may open the door for 1-1.7μm communication wavelength ISBT devices. Here the negative differential resistance of RTD and the ISBT absorption were evaluated. And for the growth, the polarity control of Ga-polar GaN was realized on sapphires with RF-MBE, by use of high-temperature grown AlN nucleation layers (HT-AlN-NL) at 750-950°C. The Ga-polar GaN showed a smooth surface morphology. We fabricated two kinds of AlN/GaN RTD structures on MOCVD-GaN templates; one is double barrier (DB-) type, i.e. two 1nm AlN barriers and 0.75nm GaN well, and the other is superlattice barrier (SLB-) type, having six 1nm AlN barriers and five 1nm GaN wells. The current-voltage characteristics were evaluated at the room temperature. For the SLB-RTD, the negative differential resistance with a peak-valley ratio of 9.7 and peak current density of 150A/cm^2 were observed at 1.6V. Secondly, in order to investigate the ISBT, 54 pair of GaN (6ML)/AlN(12ML) superlattices were prepared directly on (0001) sapphire substrates using the HT-AlN-NL mentioned above. The light transmission spectra of superlattice had a clear sharp dip around 1.3μm in wavelength. And AlGaN/GaN HEMTs with the high electron mobility was demonstrated. These results may show the possibility of RF-MBE in the fabrication of high-performance AlGaN quantum heterojunction devices. This work is supported by RFTF program of JSPS (No. JSPS-RFTF97P00102).

9:00 AM *I1.2
SURFACE STRUCTURES AND GROWTH KINETICS OF GaN (0001) AND (000$\bar{1}$) SURFACES. R.M. Feenstra, H. Chen, C.D. Lee, Dept Physics, Carnegie Mellon University, Pittsburgh, PA; J. Neugebauer, Fritz-Haber-Institut, Berlin, GERMANY; J.E. Northrup, Xerox PARC, Palo Alto, CA.

The structure and formation of GaN (0001) and (000$\bar{1}$) surfaces grown by plasma-assisted molecular beam epitaxy are discussed. Reconstructions of the bare surfaces, as well as of surfaces containing In and Si are examined in detail. Experimental results from scanning tunneling microscopy allow us to broadly determine the characteristics of the surface structures, and first principles theory is then used to determine the precise atomic arrangements. In contrast to other semiconductor surfaces, a central feature of the GaN reconstructions is their tendency to form metallic overlayers of Ga or In atoms. Strain relaxation of these terminating layers of metal atoms leads to a rich variety of surface structures, including incommensurate "fluid-like" Ga layers on the GaN(0001) surface, and an array of vacancy islands on the InGaN(0001) surface. The terminating layers of metal atoms also leads to novel aspects of the surface kinetics - N atoms are found to diffuse easily between the metal layers, thus yielding enhanced surface diffusivity for those surfaces which are terminated by more than one layer of metal atoms.

10:00 AM I1.3
GROWTH KINETICS OF AlGaN FILMS BY MBE AND ITS INFLUENCE ON COMPOSITION, CHEMICAL ORDERING AND OPTICAL PROPERTIES. E. Iliopoulos, K.F. Ludwig Jr., T.D. Moustakas, Boston University, Dept of Electrical and Computer Engineering and Dept of Physics, Boston, MA.

AlGaN films were grown by plasma assisted molecular beam epitaxy on sapphire substrates with growth rates varying from 0.2 to 1.0 mm/hr. The polarity of the films was controlled by varying the nucleation steps prior to growth. The kinetics of growth was investigated in-situ using reflection high energy electron diffraction (RHEED), optical reflectance (OR) and desorption mass spectroscopy (DMS). The film properties were determined ex-situ by Rutherford backscattering spectroscopy (RBS), x-ray diffraction (XRD), scanning electron microscopy (SEM), atomic force microscopy (AFM), chemical etching, optical reflection/transmission and cathodoluminescence (CL). The kinetics of growth were systematically investigated as a function of substrate temperature, group-III to group-V flux ratio and growth rate. It was found that the surface lifetime and diffusion length of Ga adatoms increases monotonically with the ratio of group-III to group-V fluxes. Correspondingly, the surface morphology of the films changes from statistically rough to atomically smooth. The sticking coefficient of Ga atoms, at constant growth temperature and constant nitrogen flux, was found to decrease monotonically with the total group-III flux from practically one to zero. Under group-III rich growth conditions Ga atoms segregate at the surface, effectively acting as a surfactant. These phenomena can be consistently modeled as a function of growth temperature, III/V flux and growth rate, permitting accurate control of the AlGaN film composition. Structural studies of these films reveal the existence of spontaneous chemical ordering with various superlattice structures. The degree of ordering is a strong function of the kinetic conditions of growth as well as of crystal polarity. Two monolayer superlattice ordering was found to be promoted by higher group-V to group-III flux ratio and N-polarity, while seven monolayer superlattice ordering was observed under higher III to V flux ratio. The optical constants of the films (real and imaginary part of the refractive index) were investigated by transmission/reflection experiments and analysis consistent with the Kramers-Kronig relations, resulting in accurate determination of the bandgap and the Urbach edge. Chemical ordering was found to reduce the energy gap by as much as 500 meV and sharpen the Urbach edge.

10:15 AM I1.4
IMPACT OF In CONTENT ON THE STRUCTURAL AND OPTICAL PROPERTIES OF (In,Ga)N/GaN MULTIPLE QUANTUM WELLS GROWN BY PLASMA-ASSISTED MOLECULAR BEAM EPITAXY. Patrick Waltereit, James S. Speck, University of California at Santa Barbara, Materials Department, Santa Barbara, CA; Noad A. Shapiro, Eicke R. Weber, Lawrence Berkeley National Laboratory and University of California at Berkeley, Berkeley, CA.

We investigate the synthesis of (In,Ga)N/GaN multiple quantum wells (MQWs) by plasma-assisted molecular beam epitaxy as well as their structural and optical properties. Two Ga sources are employed in order to achieve metal-stable conditions throughout deposition of the structures, thus, avoiding metal-rich grown wells and/or N-rich grown wells. This growth strategy leads to the formation of smooth interfaces and the absence of accumulated metal at the growth front. The structural parameters of these samples are extracted by high-resolution x-ray diffraction (HRXRD) in conjunction with simulations based on dynamical diffraction theory. Excellent agreement of experimemtal data and simulation reveals smooth and abrupt interfaces and a high periodicity. This finding is confirmed by atomic force microscopy. The samples exhibit smooth surfaces with large terraces, therefore, resemling the surfaces of our GaN buffer layers. We concentrate on a series of samples grown under nominally identical conditions except for the In flux. From our HRXRD experiments we conclude that the samples exhibit very similar structural parameters but different In contents ranging from 2.5% up to 12%. The optical properties of this sample series are investigated by continuous-wave photoluminescence (PL) at room temperature. The transition energy shifts to the red with increasing In content in quantitative agreement with the changes of the (In,Ga)N bandgap and the internal electrostatic fields in these structures as confirmed by self-consistent Schroedinger-Poisson calculations (SCSPCs). For further examination of the electrostatic fields we measure the transition energy versus externally applied biaxial tension. While the PL energy shifts to the red for low In contents we observe a blue-shift for the highest In contents. We simulate the PL shift in SCPSCs by taking into account both the changes in well and barrier bandgap as well as the piezoelectric polarization in our samples.

10:30 AM I1.5
STUDY OF INITIAL GROWTH OF InN AND InN-BASED HETEROSTRUCTURES BY MOLECULAR BEAM EPITAXY. Hai Lu, William J. Schaff and Lester F. Eastman, Department of Electrical and Computer Engineering, Cornell University, Ithaca, NY.

In this work, we prepared epitaxial InN on (0001) sapphire with an AlN buffer layer by molecular beam epitaxy (MBE). A series of samples were grown with different thickness under the optimized growth conditions. As grown films were characterized by x-ray diffraction, reflective high-energy electron diffraction, atomic-force microscopy and Hall measurements. A transition from three-dimensional to two-dimensional growth is observed. By extrapolating the curve of sheet carrier density vs. film thickness to zero film thickness, a strong residual sheet charge as high as 4.4e13cm^{-2} is derived, which may be located at the interface between the AlN buffer and the InN film or at the near-surface. Since this sheet charge is nearly independent on the quality of the AlN buffer layer used, which, if properly prepared, can improve the structural and electrical properties of the following InN significantly, it is more likely that this

is surface charge accumulation similar to what is observed at InAs surfaces. InN samples with Hall mobility more than 1200 cm^2/Vs and carrier concentration below 2e18 cm^{-3} can be routinely achieved in this study. Various InN-based heterostructures with AlInN or AlN barrier were fabricated. X-ray diffraction study clearly shows the formation of heterojunctions. The AlN barriers were prepared by migration enhanced epitaxy at low growth temperature between 150°C and 450°C. It is found that the surface morphology is improved after an AlN barrier layer is added. Hg probe was used as Schottky contact for convenience. Better rectifying behavior but larger leakage current was observed in the sample with 450°C AlN barrier, while, the sample with 150°C AlN barrier shows poorer rectifying characteristics but much smaller leakage current. This is the first study on the formation of Schottky contact on InN-based heterostructures.

10:45 AM I1.6
GROWTH OF GaN ON ELECTRICALLY CONDUCTIVE LATTICE-MATCHED ZrB_2 (0001) SUBSTRATE BY MOLECULAR BEAM EPITAXY. Jun Suda and Hiroyuki Matsunami, Kyoto Univ, Dept of Electronic Science and Engineering, Kyoto, JAPAN.

Electrically conductive substrates are desirable for group-III nitride devices with a vertical current flow, such as light-emitting devices and power switching devices. In this paper, growth of GaN on electrically conductive metal boride substrate is presented. Zirconium diboride (ZrB_2) is a semi-metal compound (several $\mu\Omega$-cm) with a hexagonal crystal structure. The a-axis lattice constant of ZrB_2 is 3.169 Å, which is almost lattice-matched to GaN (3.188 Å). High-speed bulk growth of ZrB_2 using a floating zone method has been developed by S. Otani and H. Kinoshita,[1] which makes possible to utilize this compound as a substrate. GaN was grown on a mirror-polished ZrB_2 (0001) substrate by molecular beam epitaxy (MBE) using elemental Ga and radio frequency (rf) plasma-excited active nitrogen. Epitaxial growth was confirmed by *in situ* reflection high-energy electron diffraction (RHEED) observation and X-ray diffraction (XRD) pole-figure measurement. The epitaxial relationship was $[0001]_{GaN} \parallel [0001]_{ZrB_2}$ and $[1\bar{1}00]_{GaN} \parallel [1\bar{1}00]_{ZrB_2}$.[2] A RHEED pattern became spotty just after the start of growth, indicating three-dimensional nucleation of GaN on ZrB_2 substrate. The spotty pattern was unchanged all through the growth. The surface morphology of the GaN layer was rough. Low-temperature (16 K) PL spectrum was dominated by excitonic emission as well as defect- and cubic phase-related emissions. These results suggest that nucleation control is a key to realize flat and high-quality GaN growth. The effect of low-temperature (LT)-grown GaN buffer layer was investigated. A streaky RHEED pattern was clearly observed after 1-min growth of buffer layer (~10 nm), indicating flat crystalline GaN was successfully formed on the substrate. A 1 μm-thick GaN layer was grown on the buffer layer at an elevated temperature. The PL spectrum of the GaN layer was dominated only by excitonic emission. Other properties (XRD, roughness) were also improved. [1] S. Otani and H. Kinoshita, 13th Int. Conf. of Crystal Growth, Kyoto (2001). [2] J. Suda and H. Matsunami, 13th Int. Conf. of Crystal Growth, Kyoto (2001).

11:00 AM I1.7
IN SITU UV-PHOTO-ELECTRON EMISSION MICROSCOPY (PEEM) OF GaN GROWTH ON H-ETCHED 6H-SiC(0001) SUBSTRATES. J.D. Hartman, W.-C. Yang, R.F. Davis and R.J. Nemanich, North Carolina State Univ, Dept. of Physics, and Materials Science and Eng, Raleigh, NC.

The initial growth of GaN thin films on hydrogen(H)-etched 6H-SiC(0001) substrates are explored using in situ UV-photo-electron emission microscopy (PEEM). The photo-electrons were excited with UV-light from a tunable free electron laser(FEL) at Duke university. The SiC substrate surfaces were prepared by H-etching and followed by in situ annealing at 1030°C for 15 minutes. RHEED pattern of the surface exhibited a $(\sqrt{3}x\sqrt{3})R30°$ surface reconstruction indicating a clean and atomically flat surface structure. The PEEM images of the surface showed two regions with terrace widths of ~3 μm and ~6 μm, which correspond to regions containing half unit cell height steps and full unit cell height steps, respectively. GaN films in 4-10 nm thickness were grown on the etched surfaces at 700-800°C using a gas source molecular beam epitaxy (GSMBE) system connected to the PEEM. The surfaces of the GaN film grown on SiC substrates are imaged using photo-threshold constrast. The surface morphology of the film was dependent upon the growth temperature and the step structures of the H-etched SiC surfaces. For a thinner film of ~4 nm grown at 700°C, coalescence of the film occurred at the surface region containing full unit cell high steps while three-dimensional growth at the region with half unit cell high steps led to incomplete coalescence. In particular, the PEEM images of the film grown at 800°C showed the nucleation of elongated islands along the step-terrace intersection. However, a coalesced and continuous surface was observed for a thicker film of ~10 nm. The effect of stepped SiC substrate structures on the initial stages of GaN growth is discussed in terms of energetics and growth kinetics.

11:15 AM I1.8
LOW LEAKAGE CURRENT (<100 nm) HIGH BREAKDOWN VOLTAGE (>350V) HETEROJUNCTION DIODE MADE OF AlN/Si(111) USING SURFACE-RECONSTRUCTION INDUCED EPITAXY. M. Jenkins, S. Pavuluri, and M.-A. Hasan, C.C. Cameron, Applied Research Center & The Department of Electrical and Computer Engineering, University of North Carolina, Charlotte, NC; and M.R. Sardela Jr., Center for Microanalysis of Materials, Frederick Seitz Materials Research Laboratory, University of Illinois, Urbana, IL.

AlN was grown on Si(111) using surface recon-struction induced epitaxy. The Si(111)7x7, generated after thermal cleaning of Si, was converted to aluminum induced Si(111)root3xroot3 by depositing ~0.3 ML of Al on the Si(111)7x7 surface at temperatures between 650 to 700°C. In the root3xroot3 surface configuration, Al passivates all surface Si atoms, minimizing possible interaction between the Si and the overlayer. The root3xroot3 provides the proper template for hexagonal (001) or cubic AlN growth. The growth was then conducted using thermal Al evaporation from an effusion cell and atomic nitrogen beam from an RF atomic source. X-ray diffraction showed single crystalline hexagonal AlN(001) with a full width at half maximum (FWHM), measured from the layer peak, almost equal to that of the substrate (i.e. the resolution of diffractometer) indicating highly oriented AlN layer. Epitaxial growth was achieved over a wide range of Al/N fluxes and growth temperatures extending from ~350 to 850°C. As the growth temperature was lowered and the N/Al flux ratio was increased, a second peak related to cubic AlN(001) became evident indicating growth of a thin interfacial layer of cubic AlN. AlN/Si heterojunction diode, fabricated using this method, showed a breakdown voltage in excess of 350V and a leakage current below 100 nA indicating a high quality interface.

SESSION I2: POINT DEFECTS AND DOPING
Chair: Jörg Neugebauer
Monday Afternoon, November 26, 2001
Room 302 (Hynes)

1:30 PM *I2.1
GALLIUM VACANCIES AS ACCEPTOR DEFECTS IN n-TYPE GaN LAYERS GROWN BY HYDRIDE VAPOR PHASE EPITAXY. J. Oila, J. Kivioja, V. Ranki, K. Saarinen, Laboratory of Physics, Helsinki University of Technology, FINLAND; D.C. Look, Semiconductor Research Center, Wright State University, Dayton, OH; R.J. Molnar, Massachusetts Institute of Technology, Lincoln Laboratory, Lexington, MA; Y. Park, Samsung Advanced Institute of Technology, Suwon, KOREA.

Vacancy defects in n-type gallium nitride grown by hydride vapor phase epitaxy (HVPE) on sapphire were studied using positron annihilation spectroscopy. Experiments were performed in a 300-μm thick free-standing GaN as well as in a set of samples where the thicknesses of the GaN layers on sapphire were systematically varied between 1 and 60 μm. Positron measurements reveal vacancy type defects, identified as Ga vacancies in a negative charge state. Positron trapping at other negative defects is not observed, indicating that Ga vacancies are the dominant acceptor type defects in the samples. The concentration of Ga vacancies decreases strongly, from 10^{19} cm^{-3} to below 10^{17} cm^{-3}, as the distance from the interface region increases from 1 to 60 μm. In the 300-μm thick free-standing sample the concentration of Ga vacancies is only 2×10^{15} cm^{-3}. The depth profiles of Si and O are similar to that of V_{Ga}, suggesting that the Ga vacancies are complexed with the donor impurities. However, the high vacancy concentration close to layer/substrate interface correlates also with the high dislocation density at that region. The observed Ga vacancy concentrations are in good quantitative agreement with the results of Hall [1] and DLTS [2] analysis. [1] D.C. Look *et al.*, Solid State Comm. **117**, 571 (2001). [2] Z.-Q. Fang *et al.*, Appl. Phys. Lett. **78**, 332 (2001).

2:00 PM I2.2
DIFFUSIVITY OF NATIVE DEFECTS IN WURTZITE GaN. Sukit Limpijumnong and Chris G. Van de Walle, Xerox Palo Alto Research Center, Palo Alto, CA.

Knowledge of the diffusion properties of native point defects is important to assess the likelihood of their incorporation during growth and processing; in addition, it forms the basis for understanding impurity diffusion, which is nearly always mediated by native defects. We have performed a comprehensive computational study tracking the diffusion paths of various relevant point defects. For Ga interstitials (Ga_{int}) in the 3 charge state (which is stable over a large range of Fermi levels) we find an unusual interstitialcy mechanism with a migration barrier of less than 0.8 eV, suggesting

that Ga interstitials can be mobile near room temperature. This result is in agreement with the electron paramagnetic resonance results of Chow *et al.* [1], who created the interstitials by electron irradiation at low temperature. For nitrogen interstitials, where the ground state consists of a split interstitial, we calculate migration barriers of 1.6 eV for N^{-}_{int}, which is favored under n-type conditions, and 1.4 eV for N^{3+}_{int}, which is favored in p-type. For the nitrogen vacancy (V_N), finally, we find a high migration barrier for V_N^{+} (> 4 eV), suggesting V_N^{+} will only be mobile near the growth temperature. V_N^{3+}, on the other hand, which can form in p-type material, exhibits a much lower migration barrier of 1.7 eV. We propose an explanation for this huge difference, and discuss consequences for experiment.
This work was supported in part by AFOSR under contract #F4920-00-C-0019.
[1] K.H. Chow, G.D. Watkins, A. Usui, and M. Mizuta, Phys. Rev. Lett. **85** (2000) 2761.

2:15 PM I2.3
OPTICAL PROPERTIES OF CARBON DOPED CUBIC GaN EPILAYERS GROWN ON GaAs (001) SUBSTRATE BY MOLECULAR BEAM EPITAXY. D.J. As, U. Köhler and K. Lischka, Universität Paderborn, Paderbon, GERMANY.

For advanced optoelectronic and electronic devices, like light emitting diodes (LEDs), or laser diodes (LDs) controlled p-type doping and high hole conductivity is crucial. Up to now, magnesium is used as standard dopant in molecular beam epitaxy (MBE) as well as metalorganic vapor phase epitaxy (MOVPE). However, magnesium has several disadvantages which still limit the usually reported doping efficiency of Mg in GaN to maximum hole concentrations in the upper $10^{17}cm^{-3}$. This is mainly ascribed to large acceptor ionization energy and compensation effects. MBE-growth further showed that Mg is very volatile, requires low substrate temperatures and N-rich growth conditions. Both conditions are disadvantageous for high quality epilayers, especially for the cubic phase, where N-rich conditions deteriorate the phase purity. Therefore, alternative acceptors like carbon have to be investigated. In this contribution we report on the optical properties of carbon doped cubic GaN epilayers. Successful p-type doping of cubic GaN epilayers by carbon has been performed by rf-plasma assisted molecular beam epitaxy using an e-beam evaporation source. At room temperature Hall-effect measurements of the C-doped cubic GaN epilayers gave hole concentrations and mobilities as high as 6 x $10^{17}cm^{-3}$ and 200 cm^2/Vs, respectively. Photoluminescence showed two new C-related features appearing with increasing e-beam evaporation power. A new line at 3.08 eV showed thermalization above 100 K, which is typical for a donor acceptor (D^0A^0) transition involving the shallow C_N acceptor. From the spectral energy the binding energy of the C acceptor is estimated to be about E_c = 0.215 eV. At C concentrations above $10^{19}cm^{-3}$ a deep red luminescence band appeared at 2.1 eV indicating compensation effects. Our experiments demonstrate that C indeed introduces a shallow acceptor in cubic GaN with an acceptor binding energy, which is about 15 meV lower than that observed for the Mg in cubic GaN.

3:00 PM I2.4
VIBRATIONAL SPECTROSCOPY OF GaN:Mg UNDER PRESSURE. M.D. McCluskey, Dept of Physics, Washington State Univ, WA; M. Kneissl, W. Wong, D. Treat, S. Limpijumnong, C.G. Van de Walle, N.M. Johnson, Xerox PARC, Palo Alto, CA.

The microscopic structure of Mg-H complexes in GaN has been a subject of intense theoretical and experimental investigation. In order to probe the Mg-H structure, we have studied the effect of hydrostatic pressure on the local vibrational mode (LVM) frequency. At ambient pressure, the LVM frequency is 3125 cm^{-1} [Goetz et al., Appl. Phys. Lett. 69, 3725 (1996)], which corresponds to a N-H stretching mode. In this study, Fourier-transform spectroscopy was performed on free-standing GaN:Mg,H samples in a diamond-anvil cell, with nitrogen as a pressure-transmitting fluid. The samples had been removed from their sapphire substrate by the laser-liftoff technique. The LVM frequency was measured, at liquid helium temperatures, for pressures ranging from 2 to 5 GPa. In that pressure range, the frequency shift is approximately 2 cm^{-1}/GPa. Comparison with first-principles calculations allows us to derive information about the microscopic structure of the Mg-H complex. The calculated stable configuration, which has H in an antibonding position, indeed gives rise to a frequency shift consistent with experiment. In this position the hydrogen is not crowded by neighboring atoms, resulting in a relatively small frequency shift. The bond-center position, in contrast, results in a much higher pressure derivative, which would be inconsistent with the experimental observations.

3:15 PM I2.5
NOVEL CONFIGURATION FOR ACCEPTOR-HYDROGEN COMPLEXES IN GaN. Chris G. Van de Walle, S. Limpijumnong, and J.E. Northrup, Xerox PARC, Palo Alto, CA.

Incorporation of hydrogen leads to passivation of acceptors in as-grown GaN. A post-growth anneal breaks the acceptor-hydrogen complexes and activates the acceptors. Optimizing the activation process requires careful monitoring of the presence of hydrogen-related complexes, which can be achieved with vibrational spectroscopy. In order to enable identification of all the relevant complexes, we have performed first-principles calculations of the vibrational frequencies for a variety of configurations. Anharmonic effects, which are large in the case of hydrogen vibrations, have been systematically incorporated for the first time. In the course of our investigations we have identified a configuration of the Mg-H complex that is consistent with the recent vibrational spectroscopy results of Clerjaud *et al.* [1], explaining the observation of an unusual angle of 130° between the N-H bond and the c axis. Intriguingly, the configuration responsible for this signal is *not* the lowest in energy at T=0. It is stabilized by *entropy*, which significantly lowers the free energy at finite temperatures due to a low-energy excitation. Predictions for Be-H complexes, general trends in vibrational frequencies, and other consequences for experiment will also be discussed.
This work was supported in part by AFOSR under contract #F4920-00-C-0019.
[1] B. Clerjaud, D. Côte, A. Lebkiri, C. Naud, J.M. Baranowski, K. Paula, D. Wasik, and T. Suski, Phys. Rev. B **61**, 8238 (2000).

3:30 PM I2.6
ELECTRODIFFUSION AND INTERFACIAL SEGREGATION OF H IN AlN/GaN HETEROSTRUCTURES. P. Bogusławski, IF PAN, Warsaw, POLAND, and NCSU, Raleigh, NC; J. Bernholc, NCSU, Dept of Physics, Raleigh, NC.

Electronic properties of III-nitride heterostructures are strongly influenced by the presence of high electric fields, which are of both pyro- and piezo-electric origin. The electric field leads to redistribution of free carriers and to their accumulation at the appropriate interfaces. Various manifestations of this effect (e.g. 'piezo-doping', modifications of recombination energies and of radiative lifetimes of carriers, etc.) have been investigated. We show that the electric field also affects the concentration profiles of dopants in III-nitride heterostructures. While the distribution of neutral impurities near an interface is determined by the impurity segregation energy (i.e., the energy difference between the impurity located at either side of an interface), charged impurities also experience the internal electric field. The induced electromigration may lead to accumulation of dopants at the appropriate interfaces, which would screen the field and modify the profile of free carriers. We discuss this effect for H, whose charge state depends on the Fermi level: H is positively charged in p-type samples and negatively charged in n-type samples. The calculations were carried out using a multigrid-based total-energy approach in a supercell geometry. A (GaN)/(AlN) superlattice was used, which consisted of six bilayers of GaN, pseudomorphic to GaN substrate, followed by six bilayers of AlN. We find that neutral hydrogen is slightly preferred in AlN layers, the segregation energy being 0.1 eV. In the case of charged H, its barriers for diffusion along the c-axis are modified by the electric field in the heterostructure, leading to electrodiffusion along the field direction. Moreover, the segregation energy of H depends on its charge state, due to the presence of dipole layers at interfaces. The analysis of migration and segregation of a silicon donor and a nitrogen vacancy confirms the general character of this effect.

3:45 PM I2.7
INTERACTION OF HYDROGEN WITH GALLIUM VACANCIES AND NITROGEN INTERSTITIALS IN WURTZITE GALLIUM NITRIDE. A.F. Wright, Sandia National Laboratories, Albuquerque, NM.

Hydrogen can be incorporated into GaN during growth by metalorganic chemical vapor deposition or during postgrowth processing steps needed to fabricate electronic and optoelectronic devices. Theoretical studies have shown that hydrogen is electrically active in GaN and can behave either as a donor or an acceptor, depending on the electrical activity and relative concentrations of other impurities and defects in the system. Hydrogen is remarkably stable in Mg-doped GaN and must either be removed or neutralized in order to achieve significant hole concentrations. Hydrogen is also expected to strongly bind to native defects such as gallium vacancies and nitrogen interstitials where nitrogen dangling bonds exist. In an effort to understand hydrogen interactions with these defects, we have performed first-principles calculations based on density-functional theory. The calculations show that peak binding energies are indeed quite large for these defects; 3.5 eV for hydrogen bound to a gallium vacancy and 2.1 eV for hydrogen bound to a nitrogen interstitial. However, binding energies also depend strongly on Fermi level, and significantly lower values are predicted in n- and p-type material. In addition to the binding-energy dependence on Fermi level, we will descuss atomic structures and hydrogen vibration frequencies of

hydrogen-vacancy and hydrogen-interstitial complexes. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the U.S. Department of Energy under Contract No. DE-AC04-94AL85000.

4:00 PM I2.8
SCANNING CATHODOLUMINESCENCE STUDIES OF H-BONDING IN GaN:Mg THIN FILMS. N. Missert, C.H. Seager, S.M. Myers, R.G. Copeland, B. Vaandrager, Sandia National Laboratories, Albuquerque, NM.

Scanning cathodoluminescence (SCL) studies of GaN-based thin films have provided valuable insight as to the presence of different types of defects resulting from adjusting film growth conditions. Device fabrication relies on GaN:Mg layers, which are either thermally annealed or Low Energy Electron Beam Irradiated (LEEBI) in order to obtain p-type material. The activation of Mg is thought to occur through de-bonding of H incorporated during growth, although the details of the de-bonding are still under investigation. Here weve used SCL to monitor the sub-bandgap luminescence in MOCVD grown GaN:Mg films as a function of LEEBI dose, in order to elucidate the nature of the defects formed during the H-debonding process. The extent of H de-bonding with LEEBI dose is measured by FTIR. The as-grown films display a prominent H-related emission peak with an intensity and wavelength that evolve with the LEEBI dose. The shapes of the emission peaks depend sensitively on excitation density. The peak intensities scale linearly with power for low excitation density, but non-linearly with power for higher excitation density. This evolution in the luminescence suggests that the LEEBI process changes the nature of the H bonding rather than completely removing H from the film. We note that the luminescence intensity is greatly reduced after long-time, high-temperature annealing removes the majority of H from the film. This excitation density dependence of the luminescence will be compared with that observed in unintentionally doped GaN thin films. *Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under Contract DE-ACO4-94AL85000.

4:15 PM I2.9
DEEP DEFECT INDUCED QUENCHING EFFECTS IN GaN AND AlGaN LAYERS DETECTED BY ELECTRICAL AND PHOTOELECTRICAL TECHNIQUES. H. Witte, A. Krtschil, M. Lisker, E. Schrenk, A. Kielburg, J. Christen, A. Krost, Otto-von-Guericke-University Magdeburg, Institute of Experimental Physics, Magdeburg, GERMANY; B. Kuhn, F. Scholz, Universität of Stuttgart, Stuttgart, GERMANY.

Deep defect states in GaN layers show complex recharching kinetics resulting in quenching effects of thermal emissions or optical transitions. This is of fundamental importance for both device applications and basic understanding of the deep defects. N-type undoped and Si-doped GaN and AlGaN layers grown by metal-organic vapor phase epitaxy on sapphire substrates were analysed using thermally stimulated currents and photocurrent (TSC,TDP), photocurrent spectroscopy (PC) and persistent photocurrent (PPC)and optical admittance spectroscopy (OAS) at temperatures between 20 K and 500 K. As grown, implanted, and annealed layers were investigated. Specially, quenching effects of thermal emissions were observed correlating TSC experiments with photon energies above and below bandgap. Two different defects with thermal activation energies between 300 meV and 500 meV (Q1 and Q2) are involved. These defects dominate the TDP spectra under UV-light but vanish under sub-bandgap laser exposure. Using temperature dependence OAS we show that the defects Q1 and Q2 participate to the blue band. In consequence, the optical defect-to-band transitions in the blue band are quenched by additional extrinsic irradiation in PC and OAS, too, which correspond with TSC quenching. Furthermore, in PPC measurements with a second exposure during the PC decay period a quenching spectrum is formed with a main peak in this blue band. These quenching effects occur in undoped and Si-doped GaN layers as well as in AlGaN samples with Al- contents up to 21%. In conclusion, the deep defects Q1 and Q2 detected both in TSC, in PC and OAS show high quenching efficiency in all spectroscopic methods. This quenching effect were used to identify the defects in the complex spectra. Based on these results, the origin of these deep defect states are discussed in detail as metastable defect states.

4:30 PM I2.10
PHOTOLUMINESCENCE OF Zn-DOPED GaN. M.A. Reshchikov, D. Huang, H. Morkoç, Dept of Electrical Engineering, Virginia Commonwealth University, Richmond, VA; R.J. Molnar, MIT Lincoln Laboratory, Lexington, MA.

Zn compensates shallow donors in GaN, resulting in highly resistive material that can be used in electronic device fabrication. Since the most comprehensive study of the acceptor-like defects in GaN:Zn [1] the quality of the material has greatly improved. We investigated the behavior of photoluminescence (PL) in GaN:Zn in a wide range of temperatures and excitation intensities. The layers for study were grown on the c-plane of sapphire by hydride vapor phase epitaxy. Atomic force microscopy images revealed a very flat surface with atomic-layer terraces. The low-temperature PL spectrum included sharp peaks in the excitonic part with the full width at half maximum (FWHM) of about 6 meV. The peaks were attributed to a free exciton, excitons bound to a shallow donor and to the Zn-related acceptor. A blue band with a maximum at 2.9 eV and FWHM of 0.32 eV dominated in the PL spectrum at low temperatures. In contrast to the results of Monemar et al [1], we observed a significant shift (70 meV) of this band when the excitation density was varied from 10^{-5} to 100 W/cm^2, whereas the shape and the FWHM of this band remained nearly unchanged. With increasing temperature the blue band intensity quenched 10^5 times in the range 180 - 325 K. The obtained activation energy of about 0.6 eV is quite different from $\sim$0.15 eV obtained in Ref. [1]. The PL spectrum of the GaN:Zn samples under investigation contained also broad red and green bands with the maxima at about 1.8 and 2.4 eV, respectively. These bands quenched above 200 K with the activation energy of about 300 meV. The shape, position and quenching behavior of the above-mentioned PL bands were analyzed in terms of a one-dimensional configuration coordinate model. [1] B. Monemar, O. Lagerstedt, H.P. Gislason, J. Appl. Phys. 51, 625 (1980).

4:45 PM I2.11
MICRO-RAMAN STUDIES ON OXYGEN DOPED GaN GROWN BY MOLECULAR BEAM EPITAXY. D. Papadimitriou, National Technical University of Athens, Department of Physics, Athens, GREECE; A.J. Ptak, T.H. Myers, D. Korakakis, West Virginia University, Department of Physics, Morgantown, WV.

GaN films grown by molecular beam epitaxy on metal-organic chemical vapor deposited GaN templates on sapphire with different concentrations of O_2 doping were studied by micro-Raman spectroscopy. Raman spectra of O_2-doped films were evaluated with respect to spectra of unintentionally doped GaN films (n=4x10^{14} cm^{-3}) grown under the same conditions except for the O_2-flux. Reference spectra consisted mainly of E_1(TO, 561 cm^{-1}), E_2 (high frequency mode, 571 cm^{-1}), and A_1(LO, 736.5 cm^{-1}) Raman bands. Spectra of O_2-doped layers revealed that the films exhibit compressive stresses. In the case of GaN:O films (n=4x10^{19} cm^{-3}), the frequency-shift of the most intense Raman mode, the E_2, is _(_$_2$)=1.2 cm^{-1}, which implies a strain (_/_) of the order of 1x10^{-3}. At higher dopant concentrations (2.5x10^{22} cm^{-3}, determined by secondary ion mass spectroscopy) cracks were formed on the surface. Frequency-shifts between 0.7 and 0.9 cm^{-1} were observed as a function of the distance from the crack. These results will be compared with reports in the literature [1] on GaN:Si samples, where cracks are formed at a much lower concentration (n=2x10^{19} cm^{-3}) and the tensile stresses induced are almost twice in magnitude than in GaN:O. Further studies are being conducted on GaN:O samples grown at different temperatures.
[1] L.T. Romano, C.G. Van de Walle, J.W. Ager III, W. Götz, R.S. Kern, J. Appl. Phys. 87(11), 7745 (2000).

SESSION I3: POSTER SESSION
Monday Evening, November 26, 2001
8:00 PM
Exhibition Hall D (Hynes)

I3.1
GaN_xAs_{1-x} GROWTH WITH DISPERSIVE NITROGEN BY MOLECULAR BEAM EPITAXY. S.Z. Wang, T.K. Ng, W.J. Fan, W.K. Loke and S.F. Yoon, Nanyang Technological University, School of Electrical and Electronic Engineering, Microelectronics Center, SINGAPORE.

Construction of the access networks of optical fiber communication demands countless lower-price optoelectronic devices at wavelength of 1.3μm and 1.55μm respectively. GaAs-based nitride may open a promising way to supply such devices by extending its wavelength in terms of the large band-gap bowing effect. GaInAsN is an important compound, which has already been shown successful to fabricate 1.3μm laser diodes on GaAs substrates. 1.55μm laser diodes also expect to be fabricated by use of GaAs-matched GaInAsN and GaAsSbN materials. Moreover, the conduction band discontinuity of more than 300meV possibly appears at the interface of III-(V,N)/III-V heterostructure. When this property is applied to semiconductor laser, the high characteristic temperature (T_0) of over 150K has been expected. Recently, high T_0 of 148K was demonstrated in GaInAsN/GaAs quantum well lasers emitting at 1.3μm. However, it is not easy to obtain GaAs-based nitrides with reasonably high quality to fabricate laser diodes, so a number of epitaxial methods

have been applied to grow GaAsN, including metalorganic chemical vapor deposition (MOCVD), molecular beam epitaxy (MBE) and metalorganic molecular beam epitaxy (MOMBE). As known, most nitrides are remained stable at the growth temperature of MOCVD due to the strong N-X bond, therefore, it is difficult to incorporate nitrogen atom into GaAs. By virtue of plasma-assisted source technique, MBE has made it possible to obtain fairly large nitrogen concentration in GaAsN materials, in excess of 10%. But the presence of energetic ion makes the growing layers susceptible to be damaged and results in relatively poor optical properties. To avoid the bombardment effect of the energetic ion, we grow GaAsN materials in MBE system with dispersive nitrogen. This is a new growth mode other than the conventional MBE technique as well as conventional MOCVD technique. The clear streaky 2X4 refraction high-energy electron diffraction (RHEED) pattern in situ and the good double-crystal X-ray diffraction (XRD) measurement ex situ indicate the samples of high crystalline quality as well as good interface. The strong photoluminescence (PL) results serve as direct evidences to the samples of good optical properties. Results of GaAsN/GaAs quantum wells with different well width are also presented.

I3.2
GROWTH OF CARBON-NITROGEN FILMS WITH A BROAD BEAM RF ION SOURCE. David C. Ingram, Condensed Matter and Surface Science Program, Department of Physics and Astronomy, Edwards Accelerator Laboratory, Ohio University, Athens, OH; William C. Lanter, Innovative Scientific Solutions Corp., Beavercreek, OH; Charles A. DeJoseph, Air Force Research Laboratory (AFRL/PRPE), Wright-Patterson AFB, OH.

With the lack of suitable native oxides, gallium nitride based semiconductor devices will need other materials for dielectric, insulating and passivating layers in a variety of device applications. A carbon-nitrogen film is a possible candidate for this application. Insulating films can be made of this material with a variety of techniques. Ion beam techniques are a well accepted way to demonstrate the existence of a material with certain properties and a way to establish the range of those properties in the material. Ion beam assisted deposition has been used in this work to fabricate materials with various stoichiometries in order to determine the range of properties available for this material. Thin films containing predominantly carbon and nitrogen have been grown using a mixture of methane and nitrogen from a 20 cm rf ion source. The stoichiometry of the films has been measured with Rutherford Backscattering Spectroscopy (RBS), Elastic Recoil Spectroscopy (ERS), and X-ray Photo-Electron Spectroscopy (XPS). The optical and dielectric properties have also been measured. The effect of gas ratios, ion energy, and RF power on the film composition, properties, and growth rate will be reported together with an analysis of the anticipated growth mechanics.

I3.3
AlGaN/GaN PN STRUCTURES GROWN ON BULK GaN SUBSTRATES. D. Tsvetkov, Yu. Melnik, A. Pechnikov, V. Soukhoveev, V. Ivantsov, A. Syrkin, K. Tsvetkova, and V. Dmitriev, TDI, Inc., MD.

We investigated growth and properties of GaN and AlGaN/GaN pn structures grown by hydride vapor phase epitaxy on (0001)Ga face of bulk GaN substrates. The structures were grown in the temperature range from 1000 to 1100°C at atmospheric pressure. For undoped layers, concentration of electrically active uncompensated donors ranged from 1e16 to 1e17 cm^{-3}. Silicon and magnesium were used as doping impurities. AlN concentration in AlGaN layers was varied from 0 to 30 mol.%. Grown structures were characterized using x-ray diffraction, TEM, photoluminescence, SIMS depth profiling, scanning electron microscopy including electron beam induced current mode. Diode mesa structures from 100 to 800 microns in diameter were formed using reactive ion etching. Contacts were formed to n-type GaN substrate and p-type top GaN layer providing vertical device geometry. Current-voltage and capacitance-voltage characteristics were measured. Characteristics of grown structures will be presented and compared with characteristics of similar pn structures grown on sapphire substrates.

I3.4
Abstract Withdrawn.

I3.5
EFFECT OF EXCIMER LASER ANNEALING ON OPTICAL PROPERTIES OF GaN FILMS DEPOSITED BY R.F. MAGNETRON SPUTTERING. Man Young Sung, Woong-Je Sung, Yong-Il Lee, Chun-Il Park, Woo-Beom Choi, Korea Univ, Department of Electrical Engineering, Seoul, KOREA.

GaN thin films on sapphire were grown by rf magnetron sputtering with ZnO buffer layer. The tremendous mismatch between the lattices of GaN and sapphire can be partly overcome by the use of thin buffer layer of ZnO. The dependence of GaN film quality on ZnO buffer layer was investigated by X-ray diffraction(XRD) and Photoluminescence(PL). The properties of the sputtered GaN are strongly dependent on ZnO buffer layer thickness. The optimum thickness of ZnO buffer layer is around 25nm. Using Auger electron spectroscopy(AES), it was observed that the annealing process improved the GaN film quality. The surface roughness according to the annealing temperatures were investigated by atomic force microscopy(AFM) and it was confirmed that the crystallization was improved by increasing the annealing temperature. In addition, the effect of excimer laser annealing(ELA) on structural and electrical properties of GaN thin films was investigated and compared with the thermal annealed sample. Photoluminescence spectra at 8K of thermal annealed and ELA annealed GaN thin films show a near-band-edge peak at 3.2eV and 3.4eV, respectively.

I3.6
SURFACE RESISTIVITY OF MOCVD GROWN GaN THIN FILMS GROWN UNDER DIFFERENT PRESSURE. Seong-Woo Kim, Tomoki Shibata, Masahiro Akatsu, Toshimasa Suzuki, Nippon Inst of Technol, Saitama, JAPAN; Takashi Yamada, Kazuhiro Haga, Chichibu Fuji Co Ltd, Saitama, JAPAN.

Highly resistive GaN films are important as a buffer layer for field-effect transistor (FET) or high electron mobility transistor (HEMT) to avoid a parallel conductive channel that degrades device performance.
In this study we discussed the relation between the surface resistivity of MOCVD-grown GaN thin films and growth pressure. 2μm thick undoped-GaN films with 30nm thick LT-GaN buffer layer were grown in an EMCORE D-125 multi-wafer rotating disc low-pressure MOCVD system. Reactor pressure during the growth was changed from 100Torr to 300Torr.
First we measured photoluminescence spectra. The higher the growth pressure was, the stronger the band edge emission of photoluminescence was observed. The peak strength for 300Torr film was about six times stronger than that for 100Torr film. On the contrary, the full-width-at-half-maximum (FWHM) of band edge emission decreased as the growth pressure decreased. At the same time the ratio of yellow band deep level emission to the band edge emission decreased.
Then we observed the etch pit structures revealed by chemical etching using hot mixed acids of sulfuric acid and phosphoric acid (1:1, 250°C, 30min.). Three types of etch pit were observed and etch pit densities (EPDs) for all types increased as the growth pressure decreased. EPD of the film grown under 100Torr was about one order of magnitude higher than that of the film grown under 300Torr.
Finally we measured the surface resistivity by measuring the current-voltage curves. The resistivity of the film grown under 100Torr was about six orders of magnitude higher than that grown under 200Torr.
As conclusion, the lower the growth pressure is, the higher the resistivity can be obtained though the higher the defect density increases. The surface resistivity of the film grown under 100Torr was sufficiently high to be used as a buffer layer for FETs.

I3.7
Abstract Withdrawn.

I3.8
CHARACTERIZATION OF CRYSTAL POLARITY OF GaN GROWN BY METALORGANIC CHEMICAL VAPOR DEPOSITION. Ho Won Jang, Chang Min Jeon, Dept of Materials Science and Engineering, POSTECH, Pohang, KOREA; Sung Bum Kang, Jung Hee Lee, Dept of Electrical and Electronic Engineering, Kyungpook National Univ, Deagu, KOREA; Tae Hee Kang, Pohang Accelerator Laboratory, POSTECH, Pohang, KOREA; Jong-Lam Lee, Dept of Materials Science and Engineering, POSTECH, Pohang, KOREA.

The wurtzite group III nitrides are promising materials for optoelectronic and electronic devices. Understanding of their spontaneous and piezoelectric polarization properties is essential to improve the device performance, especially in InGaN/GaN-based light emitting diodes and AlGaN/GaN hetero structure field effect transistors, where the influence of polarization-induced 2-dimensional gas on the device performance is absolutely crucial. The growth of Ga-face GaN is achieved by several deposition techniques, whereas it is known until now that N-face can only be produced by molecular beam epitaxy (MBE) based processes. In this presented work, we have firstly realized N-face GaN by metalorganic chemical vapor deposition (MOCVD). The polarity of undoped Ga-face and N-face GaN films was characterized by the measurement of Schottky barrier height (SBH) on Pt contact on both samples and synchrotron radiation photoemission spectroscopy (SRPES). From I-V measurement, the values of SBH for 1-um-thick Ga-face and N-face GaN films were 1.25 $\sim$ 1.55 eV with ideality factor n = 1.23 $\sim$ 1.36 and 1.0 $\sim$ 1.20 eV with

n = 1.03 ∼ 1.59, respectively. This result is in good agreement with theoretical expectation and previous experimental results from GaN films grown by MBE. The difference in the polarity-induced band bending between both samples resulted in the change of SBH. From SRPES analysis, position of secondary electron emission edge and valence band edge was examined. As a result, the larger band bending by ∼0.8 eV was observed in Ga-face sample, which is consistent with the result from SBH measurement. Therefore we suggests that the nondestructive SRPES analysis is effective tool for the characterization of GaN polarity.

I3.9
IMPROVED EPITAXIAL GROWTH OF AlN FILMS ON SAPPHIRE BY ION BEAM ASSISTED PULSED LASER DEPOSITION. S. Six[a], B. Rauschenbach[b], [a]Universität Augsburg, Augsburg, GERMANY; [b] Institut für Oberflächenmodifizierung, Leipzig, GERMANY.

Pulsed laser deposition is a method to produce stoichiometrical AlN films. On c-sapphire substrates the hexagonal AlN films grow epitaxially with its c-axis perpendicular to the substrate. An additional low-energy argon ion bombardment can strongly improve the epitaxy of AlN on c-sapphire. The reason is an intrinsic stress caused by the ion induced defects, which reduces the lattice misfit to the substrate. The observed stress leads to an expansion of the AlN c-axis length while the a-axis length is compressed. A maximum of this lattice deformation could be observed at an argon ion energy of 500 eV for an ion incidence angle of 60°. An nitrogen ion bombardment of growing AlN films results also in highly stressed films. For this case the maximum of the lattice deformation rests at even 400 eV. With increasing growth temperature the stresses of the films decrease. Furthermore a simple model will be presented where the ion energy and growth temperature dependency of the AlN film stress is explained by the thermal activated diffusion of ion induced point defects to the surface of the growing film.

I3.10
COMBINED X-RAY SCATTERING AND STM STUDIES OF GaN NUCLEATION AND GROWTH ON SAPPHIRE. Randall L. Headrick, University of Vermont, Department of Physics, Burlington, VT; Oana Malis, Joel D. Brock, Cornell University, Department of Applied and Engineering Physics, Ithaca, NY; Christopher C. Umbach, Cornell University, Department of Materials Science and Engineering, Ithaca, NY; Min-Su Yi, Doh-Young Noh, Kwangju Institute of Science and Technology, Department of Materials Science and Engineering, Kwangju, KOREA.

We report recent studies of metal-organic MBE GaN nucleation on nitrided basal-plane sapphire. Nucleation layers were deposited from triethylgallium and atomic nitrogen at 700 degrees centigrade. An RF atomic nitrogen source was equipped with electostatic deflection plates in order to investigate the influence of energetic ionized species from the nitrogen plasma. Real-time x-ray reflectivity shows evidence for 2D growth during the first monolayer with or without ions, although the presence of ions enhances the effect. We found that under optimum conditions, a one monolayer thick buffer layer was sufficient to support subsequent growth at higher temperatures, and leads to N-polarity films as determined by x-ray standing wave analysis. We also present the first low-current STM images of GaN nucleation layers, which mainly confirm our model of nucleation based on the x-ray data.

I3.11
SURFACE ROUGHNESS AND GROWTH INSTABILITY ASSOCIATED WITH CONVENTIONAL AND PENDEO-EPITAXIAL GaN FILMS GROWN VIA MOVPE. Peter Miraglia, Amy Roskowski, Edward Preble, Sven Einfeldt, Robert F. Davis, North Carolina State University, Dept of Materials Science and Engineering, Raleigh, NC.

Results of atomic force microscopy (AFM) regarding the origins of surface roughening of GaN(0001) grown via MOVPE at 20 torr on AlN/6H-SiC(0001) substrates have revealed that a growth temperature of 1030°C and a film thickness >2.5μm produced films with the smoothest surface morphology due to a gradual reduction in the density of dislocations. Growth at 1100°C and 980°C resulted in single and multiple hillocks and uncoalesced islands, respectively, on the GaN surface. The uncoalesced islands resulted from insufficient lateral growth and island boundary impingement. All hillocks originated at pure screw or mixed dislocations that terminated on the (0001) surface; the multiple hillock originated from dislocations that terminated in close proximity. Growth of the hillocks was controlled kinetically through adatom diffusion. A hillock density of $\sim 10^6 cm^{-2}$ was observed after 15nm of growth at 1100°C on a GaN template previously grown at 1030°C. Smooth, hillock-free surfaces were also accomplished via pendeo-epitaxy (PE) at 1030°C; however, the coalescence time was increased due to a reduced lateral-to-vertical growth rate at this temperature. The $(11\bar{2}0)$ PE sidewall surface was atomically smooth after growth at 1100°C, with a root mean square roughness value of 0.17nm, reflecting the noise limited resolution of AFM.

I3.12
GROWTH AND CHARACTERIZATION OF EPITAXIAL GaN LAYERS GROWN BY CHEMICAL SOLUTION DEPOSITION. Harish Parala, Anjana Devi, Oliver Stark, Marie-Katrin Schröter, Roland A. Fischer, Lehrstuhl für Anorganische Chemie II, Organometallics and Materials Chemistry, Ruhr-Universität Bochum, GERMANY.

The application of molecular precursors to grow highly oriented GaN films by a simple technique such as chemical solution deposition is demonstrated. Nitrogen rich compounds normally used as single molecule CVD precursors (azide and amide based precursors) namely $(N_3)_2Ga[(CH_2)_3NR_2]$ (where R = CH_3 or C_2H_5) and $(NR)_2Ga[(CH_2)_3NMe_2]$ (where R = Pri) were employed to grow GaN layers by spin coating these liquid precursors on Al_2O_3(0001) substrates and subsequent pyrolysis in the temperature range 700 - 850°C. The GaN layers were characterised by detailed XRD analysis such as normal θ-2θ scans, rocking curve analysis, pole figure measurements and reciprocal space mappings. The surface morphology was analysed by SEM and composition by XPS. The optical properties of the GaN layers were studied using room temperature PL spectroscopy. The influence of the precursor molecular structure on the growth of GaN layers will be discussed in this paper.

I3.13
THREE-DIMENSIONAL MODELING OF THE HIGH PRESSURE ORGANOMETALLIC CHEMICAL VAPOR DEPOSITION OF InN USING TRIMETHYLINDIUM AND AMMONIA. Sonya McCall, Klaus J. Bachmann, North Carolina State Univ, Dept of Materials Science and Engineering, Raleigh, NC; Sam Lowry, CFDRC, Huntsville, AL.

We present a physico-chemical model of the High Pressure OMCVD process that describes the three-dimensional transport phenomena as well as gas-phase and surface reactions underlying the growth of compound semiconductors. A reduced-order process model of the Organometallic Chemical Vapor Deposition of InN from trimethylindium and ammonia at high pressures has been developed and tested. The model describes the flow dynamics coupled to chemical reactions and transport in the flow channel of a horizontal High Pressure OMCVD reactor for pressures up to 100 atm, as a function of substrate temperature, total pressure and centerline flow velocity.

I3.14
LAYER-BY-LAYER GROWTH OF GaN FILMS BY LOW-TEMPERATURE CYCLIC PROCESS. S. Koynov, P. Sanguino, M. Niehus, L.V. Melo, R. Schwarz, Departamento de Física, Instituto Superior Técnico, Lisboa, PORTUGAL; H. Alves, B.K. Meyer, Justus-Liebeg-University, Giessen, GERMANY.

Recently we have proposed a new layer-by-layer method for deposition of group-III nitrides from elemental precursors (Ga, N2) [1]. This technique is based on a two-step cyclic process, which alternates Pulsed Laser Deposition (PLD) and nitrogen plasma treatment. We have shown that such a process allows to control independently the structure and the N-content of the growing film. The objective of this work is to develop the cyclic process for achieving high quality ultra-clean GaN films. We explore the opportunities to grow stoichiometric epitaxial films on various substrates at relatively low temperatures (500°C to 700°C). This gives us the possibility to use ZnO epitaxial layers as a buffer without thermal degradation. We also show some preliminary experiments on growth over laser patterned trench structures on ZnO sublayers. Optical transmission spectra, X-ray diffraction, Atomic Force Microscopy and Photoluminescence are some of the tools used to characterise and compare the deposited films. [1] S. Koynov, P. Sanguino, M. Niehus, L.V. Melo, R. Schwarz, Layer-By-Layer Deposition of Group-III Nitrides By Two Step Cyclic Process, presented at E-MRS Spring Meeting (2001), Strasbourg, France. To be published in Materials Science & Engineering.

I3.15
SIMULATION STUDY ON FLOW STABILITY OF LOW PRESSURE MOVPE PROCEESS FOR III-NITRIDES. A. Kinoshita[a,b], H. Hirayama[a], M. Takahashi[b], A. Hirata[b], Y. Aoyagi[a]; [a]The Institute of Physical and Chemical Research (RIKEN), Saitama, JAPAN; [b]Dept of Chemical Engineering, Waseda Univ, Tokyo, JAPAN.

Mathematical modeling and numerical simulation study of a horizontal low-pressure metalorganic vapor phase epitaxy (MOVPE) reactor for III-nitrides were performed in order to predict the effect of the operating conditions on the flow stability in the reactor. The

MOVPE crystal growth of III-nitrides are considered to be more difficult than that of other III-V semiconductors. One of the main reasons of the difficulty is the strong buoyancy flow caused by the high crystal growth temperature. Therefore many ideas are proposed in order to suppress the buoyancy flow with regard to MOVPE reactors of III-nitrides. However, the theoretical engineering manners are not established yet. In this report, the effect of the operating conditions on the flow stability in the III-nitride MOVPE reactor is investigated numerically in order to establish the theoretical engineering manners for the reactors. The two-dimensional momentum, energy, and material equations were solved for N_2, H_2 and NH_3 under typical growth conditions of GaN film. The transport rate coefficients such as viscosity, thermal conductivity, and diffusivity with the changes in temperature, pressure and the composition of reactant gases in the reactor were taken into account. The unsteady flow is formed under low total gas flow rate and high nitrogen compound conditions. This is because of the strong buoyancy flow caused by the high susceptor temperature. The unsteady flow does harm to the quality of the grown crystal. The unsteady flow transitioned into steady flow conditions with increasing of total gas flow rate. The critical total flow rate at the flow condition transition depends not only on the growth temperature but also on the gas species. In conclusion, the optimization of the total gas flow rate and the carrier gas compounds are required in order to suppress the strong buoyancy flow for MOVPE growth of III-nitrides.

I3.16

TRANSITION-METAL NITRIDE TEMPLATES FOR EPITAXIAL GROWTH OF GaN AND ITS ALLOYS. Rob Armitage, Henning Feick, Qing Yang, Eicke Weber, University of California, Berkeley, Department of Materials Science and Engineering, and Lawrence Berkeley National Laboratory, Materials Science Division, Berkeley, CA; Satoko Shinkai, Katsutaka Sasaki, Kitami Institute of Technology, Department of Materials Science, Kitami, JAPAN.

Transition-metal nitride compounds exhibit several characteristic properties that are advantageous for their application as templates for epitaxial growth of III-N semiconductors. Potential benefits include close matching of lattice constant and thermal expansion coefficient with GaN, as well as high-temperature chemical stability. We tested the feasibility of this approach by growing GaN on several transition-metal nitride templates using plasma-assisted MBE. The templates are thin films deposited epitaxially by physical vapor deposition on silicon and other commercially available substrates. Photoluminescence and x-ray diffraction results for the first GaN epilayers grown on transition-metal nitride/silicon templates are encouraging. With no attempts at growth optimization for the alternative substrates, we already achieved GaN epilayer quality comparable to our optimized layers on sapphire.

I3.17

STRUCTURAL AND OPTICAL CHARACTERISTICS OF LATERALLY OVERGROWN GaN PYRAMIDS ON (111) Si SUBSTRATE. Yong-Hoon Cho, Chungbuk National University, Department of Physics, Cheongju, KOREA; H.M. Kim, T.W. Kang, Dongguk University, Quantum-Functional Semiconductor Research Center and Department of Physics, Seoul, KOREA; J.J. Song, Oklahoma State University, Center for Laser and Photonics Research and Department of Physics, Stillwater, OK; W. Yang, Honeywell Technology Center, Plymouth, MN.

Structural and optical characteristics of laterally overgrown GaN pyramids on a (111) Si substrate was investigated by scanning electron microscopy, transmission electron microscopy (TEM), and cathodoluminescence (CL) microscopy and spectroscopy. Single-crystal GaN/AlN layers were grown on (111) Si substrates by low-pressure metal-organic chemical vapor deposition (MOCVD). Then, a 0.1-μm-thick Si_3N_4 masking layer was deposited on the GaN/AlN layers by plasma-enhanced chemical vapor deposition, and an array of openings was created by photolithography and reactive ion etching. The openings were arranged in a hexagonal pattern with a 20-μm spacing and the average diameter of the openings was 5 μm. A two-dimensional array of GaN pyramids were formed by selective lateral overgrowth in the MOCVD system. Cross-sectional TEM images revealed that the threading dislocation density over the window openings is initially very high, but gradually decreases with increasing GaN thickness, and that dislocations observed over the mask are parallel to the mask interface. Top-view and cross-sectional-view CL images taken at different emission wavelengths clearly showed significant differences between the overgrown areas on top of the mask and the coherently grown regions over the windows. The CL peak intensity ratio of band-edge-emission to yellow luminescence was also investigated as a function of position in the GaN pyramid cross section. We demonstrated that there exists a strong correlation between structural defects and optical properties in laterally overgrown GaN pyramids on (111) Si substrate.

I3.18

THE CHARACTERISTICS OF A FREE-STANDING GaN SUBSTRATE GROWN BY LOW-PRESSURE METALORGANIC-HALIDE VAPOR PHASE EPITAXY (LP MO-HVPE). Seogwoo Lee, Chinkyo Kim, Juok Seo, Meoungwhan Cho, and Shi-Jong Leem, Optoelectronics Group, LG Electronics Institute of Technology, Seoul, KOREA; Seon Tai Kim, Division of Advanced Materials Engineering, Taejon National University of Technology, Taejon, KOREA.

GaN is one of the most promising materials for optoelectronic devices as well as high-power and high-temperature devices. GaN has been successfully grown by metalorganic chemical vapor deposition (MOCVD) and molecular beam epitaxial (MBE) techniques on a sapphire substrate. However, heteroepitaxial growth still remains as problems in getting high quality GaN, because it is limited with a high density of dislocation and strain due to a large difference in lattice constants and thermal expansion coefficients between hetero-epilayer and substrate. With increasing needs of high performance III-Nitrides optoelectronic devices, there are more demands on a lattice-matched substrate for GaN. Even though many different approaches have been made, a free standing GaN substrate grown by halide vapor phase epitaxy (HVPE) is currently one of the most promising substitute candidate for a sapphire or SiC substrate in comparison with other methods. The quality of HVPE-grown GaN should be, however, much more improved in many aspects for further application. In particular, a reduction of micro crack density with a minimal bending and a crystallographically flat surface should be accomplished. In this work, we report on the characteristics of a free-standing GaN grown by low-pressure HVPE on a sapphire substrate, which was eliminated after a growth, using a buffer layer grown by MOCVD. Employing custom-designed gas injection nozzles, uniformity and crystalline quality of GaN film was greatly enhanced. The improved characteristics of a free standing GaN obtained by use of low-pressure HVPE and MOCVD-grown buffer layer will be discussed in detail. In addition, a novel method of removing a sapphire substrate in order to fabricate a free standing GaN was employed so that the curvature of bending and micro crack density in a detached GaN film was notably reduced.

I3.19

APRIORI PROCESS - PROPERTY RELATIONSHIPS OF GaN EPITAXIAL GROWTH IN Ga/N/H/C/O SYSTEMS.
Constantine Loukeris, Shumaila Khan and Christos G. Takoudis, University of Illinois at Chicago, Dept of Chemical Engineering, Chicago, IL.

A comprehensive thermodynamic analysis has been performed for the Ga/N/H/C/O system from which apriori process-property relationships of the epitaxial growth of Gallium Nitride (GaN) are obtained. The parameter space for pure GaN growth is studied for five orders of magnitude of the system water vapor level, ten orders of magnitude of system pressure ($10^{-5} - 10^{5}$ Torr), five orders of magnitude of N/Ga feed ratio (1 - 100,000), and two orders of magnitude of C/Ga feed ratio (0 - 100) and H_2/Ga feed ratio (100 - 10,000). Water vapor impurities up to 10 ppm in the feed stream are predicted to have no effect on the deposition of GaN. Higher growth temperatures for pure GaN are predicted at high operating pressures, low C/Ga feed ratios, high carrier gas flow rates, and low N/Ga feed ratios. Because relative C/Ga, N/Ga and H_2/Ga feed ratios have been considered, the predictions in this study are applicable to any multiple and single precursor systems. Such analyses are applied to the molecular beam epitaxy of GaN too (C/Ga = 0). Experimental data reported on the growth of GaN are found to be in good agreement with our theoretical predictions, for numerous systems that include different source species.

I3.20

GROWTH OF GaN EPILAYERS ON Si(111) SUBSTRATES USING MULTIPLE BUFFER LAYERS. S. Haffouz, P.R. Hageman, A. Grzegorczk, V. Kirilyuk and P.K. Larsen, Exp. Solid Physics III, Research Institute for Materials, University of Nijmegen, Nijmegen, THE NETHERLANDS.

We demonstrate the growth of high quality GaN films on Si(111) substrates by MetalOrganic Chemical Vapour Deposition using two different combinations of buffer layers. The first one consists of an optimised AlN buffer layer followed by a 1 μm-thick GaN film, on which we deposited SixNy/GaN intermediate layers. The second one is an AlN buffer layer directly followed by AlGaN/GaN superlattices. The total thickness of all GaN epilayers was 3 μm. X-ray diffraction, photoluminescence and atomic force microscopy were used in order to elucidate the effectiveness of these growth processes. The resulting GaN layers are of high quality as compared to those grown directly on an optimised AlN buffer layer. In both cases, photoluminescence spectra are dominated by a strong peak related to the donor bound exciton with a full width at half maximum (FWHM) of about 50 meV at room temperature and 10 meV at 4K. The FWHM of the

symmetric (0002) rocking curves in ω-scan is about 640 arcsec. The root-mean-square roughness, as measured by atomic force microscopy, does not exceed 10 $\AA$ (18.7x18.7 μm^2).

I3.21
DOUBLE PENDEO-EPITAXIAL GROWTH OF GaN FILMS WITH LOW DENSITY OF THREADING DISLOCATION. Young Kue Hong, Hung Sub Jung, Chang-Hee Hong, Dept. of Semiconductor Science and Technology and Semiconductor Physics Research Center, Chonbuk National University, Chonju, KOREA; Min Hong Kim and Shi-Jong Leem, Department of OE Team, Device & Materials Laboratory, LG Electronics Institute of Technology, Seoul, KOREA.

Conventional pendeo-epitaxy approach of GaN without a dielectric mask has been developed as a simple approach of growing thin films with low densities of threading dislocations and no tilting in the coalesced region. However, high defect densities in vertical growth region originating from (0001) direction of GaN seed layer was still found. We report on an alternative method as a double pendeo-epitaxy technique for growing uniformly GaN thin films with low defect densities over the entire surface of a substrate. Each pendeo-epitaxal GaN and the underlying GaN seed layer were grown in a horizontal low-pressure metalorganic chemical vapor deposition. The first GaN seed layer were formed 8.5μm-wide rectangular stripes oriented along the [1-100] direction with a 12.5μm period with conventional photolithography and reactive ion etching. The first pendeo-epitaxial growth behavior of GaN was strongly related with growth temperature and TMGa flow rate. Optimized growth conditions are growth temperature of 1160°C, growth pressure of 76 torr and TMGa flow rate of 75 μmol/min, respectively. After coalescing over the surface area, the relatively high defect region originating from (0001) direction of grown layers was removed by the same process described above, following by the second pendeo-epitaxial growth. From the analysis of atomic force microscopy images, no different surface steps in the coalesced area were found and the termination of surface steps by threading dislocations were not observed at the regrown GaN layers. That results imply low density of threading dislocation on the GaN surface. The RMS roughness was 0.271 nm. The ratio of the FWHM perpendicular to parallel case to the stripe is almost unity. Also the isoelectronic In doping during the growth were found to critically affect on the strain relaxation. The structural and optical properties of double pendeo-epitaxial grown layers will be discussed more in the conference.

I3.22
V - III RATIO EFFECT ON CUBIC GaN GROWN BY RF PLASMA ASSISTED GAS SOURCE MBE. Li-Wei Sung, and Hao-Hsiung, Lin National Taiwan University, Dept of Electrical Engineering, Taipei, TAIWAN, ROC; Chih-Ta Chia, National Taiwan Normal University, Dept of Physics, Taipei, TAIWAN, ROC.

We report the growth and characteristics of cubic GaN films deposited on (001) GaAs substrates by using RF plasma assisted gas source MBE. The films were deposited at different V to III ratios to investigate the effects on structural and optical quality. By inspecting the surface conditions and thickness of GaN films grown on a three-inch wafer without rotation, we found three different growth regions, namely, Ga droplet, intermediate Ga stable, and N stable region, existing across the wafer. Optical properties of the films grown on these three regions were compared by using photoluminescence (PL). Micro-Raman scattering were also performed to analyze the crystallinity of the films. Both results show that film quality is improved as the Ga-flux increases. But over rich Ga-flux results in Ga accumulation on the sample surface and the introduction of wurtzite GaN. From the experimental results, we show that rather the optimal growth condition for cubic GaN at Ts = 720°C is just on the boundary of intermediate Ga stable region and Ga droplet region. Detailed results of PL and micro-Raman will be discussed.

I3.23
MICROSTRUCTURE OF ELO-GaN LAYERS GROWN BY HYDRIDE VAPOR PHASE EPITAXY. S. Gradečak, K. Leifer, P. Stadelmann, Centre Interdepartemental de Microscopie Electronique, École Polytechnique Fédérale de Lausanne (EPFL), Lausanne, SWITZERLAND; V. Wagner, O. Parillaud, M. Ilegems, Institut de Micro et Optoélectronique, Département de Physique, EPFL, Lausanne, SWITZERLAND.

Electron microscopy techniques are applied to investigate structural properties of the GaN layers grown by a selective epitaxy. Hydride vapor phase epitaxy (HVPE) in combination with epitaxial lateral overgrowth (ELO) produces high quality GaN layers on sapphire with low dislocations density, high growth rates and good selectivity. Influence of the carrier gas (hydrogen vs. nitrogen), V/III ratios, stripe directions and seed layer structures (crystalline vs. amorphous) on defects characteristics were investigated. Metal organic vapor phase epitaxy (MOVPE)-GaN(0001)/Al_2O_3 (0001) buffer layers were patterned with SiO_2 stripes. The GaN stripes are formed during the initial stage of the growth that is performed using hydrogen/nitrogen mixtures as a carrier gas. The cross sections of the stripes can be modified during the growth by varying the carrier gas composition. The resulting rough surface is subsequently flattened using pure nitrogen. During the lateral growth threading dislocations from the buffer layer bend from vertical direction of propagation. Bending behavior depends on the type of dislocation and on the shape of the GaN film in the initial stage of the growth. The difference in the stoichiometric conditions during the growth on the top and lateral facets of the GaN stripes forms well-defined regions within the ELO-GaN films. Differences in optical properties of these regions are ascribed to the change in the density of threading dislocations and point defects.

I3.24
QUANTITATIVE DEFECT ANALYSIS OF GaN THICK FILMS BY TEM AND AFM. Praveena Bhaskara, Changmo Sung, Dept. of Chemical Engineering, Center for Advanced Materials, University of Massachusetts, Lowell, MA; David Bliss, Mike Suscavage, Air Force Research Laboratory, Hanscom AFB, MA.

Ever since the discovery of the astonishing properties of GaN, many research groups have been involved in the processing of the perfect GaN crystal. Hallide vapor transport (HVT) technique was employed to grow GaN epilayer on a MOCVD pre-deposited buffer layer. The uniqueness of our process is the deposition of the buffer layer itself in two steps: low temperature and high temperature. This new epitaxial system was characterized by TEM, AFM and X-ray diffractometer. Microstructure and electrical properties of the GaN thick films were seen to be changing as a function of growth temperature. AFM of the buffer layers showed that the rougher buffer layers produced better epilayers due to the presence of islands. TEM performed on the cross-section, as well as the plan view, of the samples showed a remarkable decrease in the dislocations in the current system, compared to the samples that were solely deposited by MOCVD. This fact was confirmed by the FWHM of the X-ray rocking curves of the respective samples. Decrease in the dislocation density as a function of distance from the buffer layer-epilayer interface, showed a good control over the HVT process. The improved electrical properties of this system were verified by electron mobility tests, showing a peak activity at 1070°C growth temperature. Advanced analytical methods of polarity and dislocation density measurements have been established to understand the relation between microstructure and electrical properties of the thick film GaN.

I3.25
EFFECT OF ADDITIONAL HCl ON THE SURFACE MORPHOLOGY OF HIGH QUALITY GaN ON SAPPHIRE BY HVPE. X.Q. Xiu, R. Zhang, D.Q. Lu, Z.W. Wang, S.L. Gu and Y.D. Zheng, Department of Physics, Nanjing University, Nanjing, P.R. CHINA.

The polarity of GaN is known to be an important factor in determining the surface roughness and properties of the as-grown material such as chemical reactivity. And precise control of the growth in polar direction is necessary to obtain low defect density materials as well as a specular surface. In this study, we obtained high quality GaN with smooth surface on sapphire by adding the additional HCl into the HVPE growth process. The result is attributed to the control of polarity of GaN films during growth. GaN films were grown in a conventional horizontal hydride vapor phase epitaxy reactor. These films were directly deposited on sapphire substrates and additional HCl flow with main N_2 was simultaneously introduced into the mixing zone. No buffer layers or other nucleation step or GaCl pre-treatment have been used. Photoluminesence, High-resolution X-ray diffraction (rocking curves), atomic force microscopy (AFM) and scanning electron microscope (SEM) analysis were performed for determining the properties of these crystal films. AFM and SEM observation of the GaN surface showed smooth surfaces with few morphology features. There are two types of hexagonal facet morphologies: smooth facets and few pointed facets (pyramid). The strong band-edge emission as well as yellow emission was observed. Wet etching experiments showed that the (0001) polarity of GaN is obtained. The additional HCl altered the equilibrium at the GaN growth front, and the reversible reaction decreased the nucleation density or growth rate. Further, lower growth rate promote the surface diffusion and the coalescence over (0001) plane. Probably additional HCl improved the surface morphology by suppressing the (000-1) polarity growth in the initial stage of the growth.

I3.26
Abstract Withdrawn.

I3.27
WHITE BEAM SYNCHROTRON X-RAY TOPOGRAPHY AND X-RAY DIFFRACTION MEASUREMENTS OF EPITAXIAL

LATERAL OVERGROWTH OF GaN. W.M. Chen, P.J. McNally, Microelectronics Research Laboratory, Research Institute for Networks and Communications Engineering (RINCE), Dublin City University, Dublin, IRELAND; K. Jacobs, Department of Information Technology (INTEC), University of Gent, BELGIUM; T. Tuomi, Optoelectronics Laboratory, Helsinki University of Technology, FINLAND; A.N. Danilewsky, Freiburg, GERMANY; D. Lowney, J. Kanatharana, Microelectronics Research Laboratory, Research Institute for Networks and Communications Engineering (RINCE), Dublin City University, Dublin, IRELAND; L. Knuuttila, J. Riikonen, Optoelectronics Laboratory, Helsinki University of Technology, FINLAND.

Epitaxial Lateral Overgrowth (ELO) of GaN on Al_2O_3 using a SiO_2 mask with different fill factors (ratio of stripe opening width to stripe period) are examined with White Beam Synchrotron X-ray Topography (WBSXT) and X-ray rocking curve analysis. The sapphire substrate was identified with a dislocation density of the order of $\sim 10^6 cm^{-2}$. WBSXT in both transmission and back reflection mode is used to image the ELO GaN topograph and confirms that crystal planes in the lateral overgrown part (wing) are tilted, and the wing tilt increases with the fill factor. X-ray rocking curve and WBSXT measurements confirm the same wing tilt tendency as the fill factor changes. The WBSXT method provides a measure of the maximum wing tilt, while the X-ray rocking curve method gives the average wing tilt. The average wing tilt reaches about 1602 arcsec at a fill factor of 0.625, but the maximum wing tilts can reach values as large as 2372 arcsec when the fill factor is only 0.571. This study shows that WBSXT is an effective method in dislocation and wing tilt determination for the GaN on Al_2O_3 ELO epilayer system or indeed for similar systems.

I3.28
GROWTH OF GaNSb MBE-LAYERS. P. Cristea, K.W. Benz, D.G. Ebling, Freiburg Materials Research Center, University of Freiburg, GERMANY.

The single crystalline growth of the GaNSb system is difficult due to the miscibility gap expected for nearly the whole composition range for thermodynamic equilibrium conditions. The gap is determined by the differences of the atomic radii and of the electronegativities for N and Sb. To overcome this problem crystal growth has to be performed under non-equilibrium conditions with kinetically controlled growth, which is the case for MBE growth. It has been demonstrated already for the growth of the GaAsN-system exhibiting a similar large miscibility gap. GaNSb-layers were grown on Si(111)-substrates by MBE using NH3 as a N-source and solid element sources for Ga and Sb. The parameter window for growth was limited due to side reactions like the decomposition of NH3, the desorption of at high temperature volatile compounds like Sb and GaSb or the reaction of Sb with NH3. The composition of the layers was analyzed by XRD and RBS. Antimony bulk concentrations of up to 2% could be obtained in GaN. Higher concentrations of antimony are observed at the surface of the layers indicating an antimony segregation. The surface concentration of antimony seems to be more or less independent of the bulk concentration and the flux of antimony. Optical characterization of the samples was performed by PL and CL measurements, as well as absorption measurements.

I3.29
BAND-GAP ENGINEERING IN SPUTTER-DEPOSITED $Sc_X Ge_{1-X} N$. M.E. Little, M.E. Kordesch, Condensed Matter and Surface Science Program, Dept. of Physics and Astronomy, Ohio University, Athens, OH.

Reactive sputtering was used to grow thin films of $Sc_x Ga_{1-x} N$ with scandium concentration of 20%-70% on quartz substrates at temperatures of 300-675 K. X-ray diffraction (XRD) of the films showed either weak of no structure, suggesting the films are amorphous or microcrystalline. Optical absorption spectra were taken of each sample and the optical band gap was determined. The band gap varied linearly with composition between 2.0 and 3.5 eV. ScN and GaN have different crystal structures (rocksalt and wurzite, respectively), and thus may form a heterogeneous mixture as opposed to an alloy. Since the XRD data were inconclusive, bilayers of ScN/GaN were grown and optical absorption spectra taken. A fundamental difference in the spectra between the bilayer films and alloy films was seen, suggesting the films are alloys not heterogeneous mixtures.

I3.30
GROWTH OF GALLIUM NITRIDE TEXTURED FILMS AND NANOWIRES ON POLYCRYSTALLINE SUBSTRATES AT SUB-ATMOSPHERIC PRESSURES. Hari Chandrasekaran and Mahendra K. Sunkara, Department of Chemical Engineering, University of Louisville, Louisville, KY.

Substrate independent methods for growing large area, single crystal quality gallium nitride films are of great interest to eliminate the requirement of expensive lattice-matching substrates. In this regard, we report a process for the growth of textured gallium nitride films on polycrystalline pyrolytic-boron nitride (PBN), quartz and alumina substrates. In this technique, we exposed a thin film of gallium with thickness less than 5 microns to atomic nitrogen using ECR-MW plasma source. The substrate was resistively heated to an approximate temperature of 900°C. The average size of crystals after a typical growth experiment was between 5 - 20mm. Platelet shaped crystals nucleated and self-oriented with one another to produce a thin, textured film. These films were characterized using X-ray Diffraction, cross-sectional and high resolution Transmission Electron Microscopy. The growth of GaN nanowires with diameters of 40-60 nm and 1 micron length was also observed along with a textured GaN film. High-resolution transmission electron microscopy showed that the wires to be single crystalline without any defects. Electron energy loss spectroscopy (EELS) and Energy Dispersive Spectroscopy (EDS) showed that the wires were free of any contamination. Funding from U.S. Air Force and the National Science Foundation (NSF) through a CAREER grant is gratefully acknowledged.

I3.31
GROWTH OF HIGH-QUALITY GAaN ON Si (111) BY ULTRAHIGH VACUUM CHEMICAL VAPOR DEPOSITION. Min-Ho Kim, Young-Churl Bang, Young-Gu Do, Chel-Jong Choi, Tae-Yeon Seong, and Seong-Ju Park, Kwangju Institute of Science and Technology, Dept of Materials Science and Engineering, Kwangju, KOREA.

The potential for integration of optoelectronics and microelectronics on a Si wafer makes studies on the epitaxy of a GaN layer on Si extremely important. In this study, we have investigated the deposition of a GaN layer on a Si (111) substrate with an AlN buffer layer, using an ultrahigh vacuum chemical vapor deposition (UHVCVD) system. Although UHVCVD has appeared to be the most promising method for low temperature growth and selective epitaxial growth of Si or Si_{1-x}/Ge_x, few studies have been reported on the III-nitride growth by UHVCVD. The reactant source materials for Ga, Al, and N were triethylgallium, trimethylaluminium, and NH_3 (99.9999% purity), respectively. A thin AlN buffer layer ($\sim$10 nm) was deposited on the Si substrate at a temperature of 830°C. The resultant AlN buffer layer showed a characteristic of a single crystalline epilayer having a wurzite structure. The substrate temperature was then decreased to 800°C under an NH_3 flow and a 1.5 μm-thick GaN layer was subsequently deposited. The low temperature photoluminescence (PL) spectra were found to have an intense excitonic emission with a full width at half maximum (FWHM) of 6.8 meV. A room temperature PL also revealed a strong bandedge emission peak having a FWHM of 33 meV, which is the narrowest value among those reported to date. The structural properties of the resultant GaN layer will also be presented using x-ray diffraction and high-resolution electron transmission microscopy.

I3.32
MICROSTRUCTURAL CHARACTERIZATION OF GaN-GaAs ALLOYS GROWN ON (001) GaAs BY MOLECULAR BEAM EPITAXY. Hyonju Kim, T.G. Andersson, M. Albrecht, W. Jäger, and N. Stolwijk, Applied Semiconductor Physics, Department of Microelectronics and Nanoscience, Chalmers University of Technology and Göteborg University, Göteborg, SWEDEN.

Among III-V semiconductor compounds, GaN-GaAs alloys have recently received much attention due to their large bowing parameter and corresponding broad span in their energy band gap. It is also interesting to note that the zinc blend GaAs1-xNx can be lattice matched to silicon when x = 0.2, where also the lattice mismatch to GaAs falls within $\sim$4%. However, the solubility of either N in GaAs or As in GaN is known to be very small, resulting in unfavorable phase separation in the grown layer. In this study, two sets of samples, each of which lies in the N-rich and As-rich end of the GaN-GaAs alloys, respectively, were investigated using transmission electron microscopy (TEM). For the GaN:As layer, TEM analysis revealed that the layer consisted of two phases, cubic and wurzite GaN. Getting far from the interface, the layers showed columnar structure, the lateral dimension of which was estimated to be 20-30 nm. Selected area diffraction (SAD) pattern showed that the columns were slightly misoriented toward each other. The dominant cubic phase at the interface region can be explained partly in terms of As surfactant effect. The arsenic in the GaN was confirmed by secondary ion mass spectroscopy (SIMS). We also fabricated thin GaAs layer with N-doping (GaAs/GaAs:N) in order to investigate not only the phase properties but also the diffusion phenomena of N in GaAs. Nanometer-size crystallites of GaN were formed in the GaAs matrix as observed by TEM. After annealing (at 905°C for 5 h) process, TEM analysis did not exhibit any noticeable change of the nm-particles. Measurements by SIMS showed only slight difference in N-distribution profile before and after the

annealing. This should be explained in a different diffusion mechanism compared with the previously reported results for a similar structure, where the N-diffusion was explained by the kick-out mechanism.

I3.33
LAYER THICKNESS DEPENDENCE OF STRAIN IN GaN GROWN BY HYDRIDE VAPOR PHASE EPITAXY.
Gyu Gwang Sim, P.W. Yu, Dept of Info and Comm, Kwangju Inst of Sci and Tech, Kwangju, KOREA; D.C. Reynolds, D.C. Look, Semiconductor Research Center, Wright State University, Dayton, OH; Sang Soo Kim and D.Y. Noh, Dept of Materials Science and Engineering, Kwangju Inst of Sci and Tech, Kwangju, KOREA.

GaN epilayers on sapphire substrates grown by hydride vapor phase epitaxy usually suffer from biaxial compressive strain due to the mismatches of the thermal expansion coefficients and the lattice constants between GaN and sapphire substrates. We have studied the layer thickness effects on strain and transition energies by photoluminesce (PL) and photoreflectance (PR). Samples used in this study have the layer thickness of 0.76, 2.6, 5.3 and 48 μm. The layer thickness dependence of strain is clearly observed by X-ray diffraction (XRD). The lattice constants were evaluated to be 5.1923, 5.1895, 5.1886, and 5.1844 Å for GaN epilayer with the thickness of 0.76, 2.6, 5.3, and 48 μm, respectively. The corresponding strains were evaluated. The strain along the c-axis (ϵ_{zz}) decreased with increasing layer thickness. This indicates the relaxation of strain with layer thickness and is attributed to the relaxation mechanism of the residual strain resulting from dislocations. The variation of transition energy with layer thickness was investigated by PL and PR. The PL and PR spectra showed the redshift of the transition energies with increasing layer thickness. This is due to strain-induced energy shift. The strain and the excitonic transition energy have linear relation of E_A=3.481 13.24ϵ_{zz} eV. Since the strain effect is very small at the layer thickness of 48 μm we expect zero strain for thicker layers.

I3.34
EFFECT OF HIGH TEMPERATURE SINGLE AND MULTIPLE AlN INTERMEDIATE LAYERS ON N-POLAR AND Ga-POLAR GaN GROWN BY MOLECULAR BEAM EPITAXY. F. Fedler, J. Stemmer, T. Rotter, D. Mistele, H. Klausing, O. Semchinova, J. Aderhold, J. Graul, Laboratorium für Informationstechnologie, Universität Hannover, GERMANY; R.J. Hauenstein, Department of Physics, Oklahoma State University, OK; A.M. Sanchez, F.J. Pacheco, S.I. Molina, Departamento de Ciencia de los Materiales e Ingenieria Metalurgica y Quimica Inorganica, Universidad de Cadiz, SPAIN.

Wurtzite GaN samples containing one, three and five 4nm thick high temperature AlN interlayers have been grown on (0001) sapphire substrates by plasma-assisted molecular beam epitaxy. N-polar as well as Ga-polar thin films then have been characterized by XRD, AFM, TEM, wet chemical defect sensitive etching, and electrical measurements.
All samples under consideration show excellent AFM rms surface roughness below 1nm (partly below 0.3nm). From TEM pictures it can be seen that AlN interlayers within GaN material alter the direction of threading dislocations or stop their further penetration altogether [1,2]. The FWHM of XRD rocking curves exhibits a minimum for Ga-polar samples with one AlN interlayer. For one AlN interlayer also, but N-polar samples, wet etching (whisker counting) reveals a minimum number of threading dislocations. Rocking curves for N-polar samples do not show significant differences.
N-polar GaN layers have been found to exhibit significantly smaller compressive strain (~0.3%) when compared to Ga polar ones (~0.5%). This is attributed to the AlN buffer deposited prior to GaN growth mandatory for Ga-polarity. A low angle tail for strained samples in XRD θ-2θ scans hints at a AlN related lattice relaxation scheme. It is uncertain whether polarity or different ammount of strain is the main reason for AlN interlayers having a different effect on the structural quality of Ga-polar and N-polar GaN layers.
Hall measurements show a rise in electron mobility due to the 2DEG at the interface between GaN and the AlN interlayers. For N-polar samples the exceptional mobility increase from 68 (no AlN interlayer) to 707 cm^2/Vs (one AlN interlayer) as well as the extremely low intrinsic carrier density of 1.25 x 10^{17} cm^{-3} proves the applicability of AlN barriers in inverted FET devices. The mobility rise in Ga-polar samples is significantly less owing to the fact that the 2DEG is situated below the GaN-AlN interface.
[1] J. Stemmer et al., J. Cryst. Growth 216, 15 (2000).
[2] A.M. Sanchez et al., Mat. Sci. Eng. B 80, 299 (2001).

I3.35
DESIGN, GROWTH AND CHARACTERIZATION OF AlGaN/AlN DISTRIBUTED BRAGG REFLECTORS FOR UV VCSELS.
A. Bhattacharyya, E. Iliopoulos, I. Sandeep, A.V. Sampath, T.D. Moustakas, Boston University, Dept. of Electrical and Computer Engineering, Boston, MA; I. Friel, Boston University, Physics Dept., Boston, MA.

As part of recent efforts to develop III-V nitride-based vertical cavity surface emitting lasers (VCSELs), several research groups are focusing on the design and fabrication of high reflectivity nitride distributed Bragg reflectors (DBRs). These have the advantage that they can be grown monolithically with the lasers active region. High reflectivity DBRs fabricated from GaN/AlGaN and GaN/AlN, for VCSELs operating in the near UV to green part of the spectrum, which would employ an InGaN multi quantum well (MQW) active region, have already been demonstrated. However, such structures are unsuitable for wavelengths less than 370nm because of absorption in the GaN layers. Here we report on the modeling and growth of AlGaN/AlN DBRs for VCSELs that would operate in the UV part of the spectrum, and use either a GaN or AlGaInN MQW active region. The DBRs were modeled using the transmission matrix method and employing refractive index data obtained from bulk films. The modeling results show that for 30% AlGaN/AlN bilayers, around 25.5 periods are required to achieve 99% reflectivity, depending on the incident medium. The DBRs were grown by MBE on (0001) sapphire. The thicknesses were monitored in-situ by RHEED intensity oscillations and optical reflectometry. The DBRs were characterized using reflectivity measurements, X-ray diffraction, SEM and TEM. We find that the number of allowed periods of the DBR is limited by strain effects due to the lattice mismatch that exists within this family of materials. Specifically, the AlN layers, having the smaller lattice constant, are subjected to a tensile stress, which for a large number of periods results in the formation of cracks. By growing the structure on a thick AlN buffer layer we were able to eliminate cracks over a significant region of the 2" wafer. One sample was measured to have a reflectivity above 95% at around 310nm.

I3.36
CFD SIMULATION OF PLANETARY MOCVD REACTORS TO INCREASE EFFICIENCY OF GROWTH OF NITRIDE LIGHT EMITTING DIODES AND LASERS. B. Schineller, M. Dauelsberg, H. Protzmann, M. Luenenbuerger, O. Schoen, M. Heuken, AIXTRON AG, Aachen, GERMANY; G.P. Yablonskii, E.V. Lutsenko, I.P. Marko, Belarussian Academmy of Sciences, Minsk, BELARUS.

The growing demand for high volume production capabilities for the MOCVD growth of nitride-based semiconductor structures requires the easy scale-up of processes from the 6 × 2 inch configuration to the 11 × 2 inch configuration. To achieve this goal process conditions were numerically modeled using "computational fluid dynamics" (CFD) model to understand the dependence of the growth rate and In-incorporation as a function of total flow and the ratio of group-V hydride and group-III metalorganics flows. The numerical simulations took into account the effect of the carrier gas and the temperature distribution in the reactor. In experimental series we achieved excellent wafer to wafer homogenities of $\Delta\lambda_{Max-min}$ = ±2 nm and run to run reproducibilities of better than 1 nm in 5 consecutive runs at a wavelength of 470 nm. To investigate the luminous efficiency and the recombination mechanisms of a series of samples with different In concentrations in the MQW high excitation photoluminescence experiments were performed using an N_2 laser with excitation power densities of up to 1 MW/cm^2. Lasing up to temperatures of 525 K and 469.5 nm was observed in edge emission geometry. The far-field patterns of the laser emission consisted of three bright spots at 30° -15° and - 45° (negative angles measured towards the substrate). The emission spots at negative angles are attributed to leaky mode emission lasing. The laser threshold increased exponentially from 170 kW/cm^2 to 900 kW/cm^2 with increasing wavelength. We will discuss the influences of growth parameters on the optical and structural properties of the wafers. Numerical modeling will be used to explain the results theoretically.

I3.37
CALORIMETRIC DETERMINATION OF THE ENTHALPY OF FORMATION OF InN AND COMPARISON WITH AlN AND GaN.
Mandar R. Ranade and Alexandra Navrotsky, UC Davis, Dept of Chemical Engineering and Materials Science, Thermochemistry Facility, Davis, CA; Franck Tessier and Roger Marchand, UMR CNRS, Verres et Céramiques, Inst de Chimie de Rennes, Univ de Rennes 1, Rennes, FRANCE.

The standard enthalpy of formation of InN at 298 K has been determined using high temperature oxidative drop solution calorimetry in a molten sodium molybdate solvent at 975 K. Calorimetric measurements were performed on six InN samples with varying nitrogen contents. The samples were characterized using X-ray diffraction, chemical analysis, electron microprobe analysis, and BET surface area measurement. The variation of the enthalpy of drop solution (kJ/g) with nitrogen content is approximately linear. The data, when extrapolated to stoichiometric InN, yield a standard enthalpy of formation $\Delta H_f{}^0$ (298 K) from the elements of -28.6 ± 9.2 kJ/mol. The relatively large error results from the deviation of individual points from the straight line rather than uncertainties in

each set of data for a given sample. This new directly measured enthalpy of formation is in good agreement with the old combustion calorimetric result by Hahn and Juza (1940). However, this calorimetric enthalpy of formation is significantly different from the enthalpy of formation values derived from the temperature dependence of the apparent decomposition pressure of nitrogen over InN. A literature survey of the enthalpies of formation of III-N nitride compounds is presented.

I3.38
CHARACTERIZATION OF G-R NOISE IN GaN FILMS GROWN BY RF-MBE ON INTERMEDIATE-TEMPERATURE BUFFER LAYERS. W.K. Fong, B.H. Leung, C.F. Zhu, Charles Surya, The Hong Kong Polytechnic Univ, Dept of Electronic and Information Engineering, HONG KONG.

We report detailed investigations of generation-recombination (G-R) noise in GaN films grown by rf-plasma assisted molecular beam epitaxy on intermediate-temperature buffer layer (ITBL) in addition to conventional low-temperature buffer layer. To characterize the film quality affected by the use of ITBL, low-frequency noise measurements were performed. The voltage noise power spectra show a strong dependence on the thickness of the ITBL. A model has been presented to explain the observed G-R noise, which stipulates that the phenomenon arises from the thermally activated trapping and detrapping of carriers by traps. The process leads to the correlated fluctuations in both the carrier number and the coulombic scattering rate. Detailed numerical evaluation shows that number fluctuation dominates in our samples. The calculated trap densities show that the use of ITBL can effectively reduce defect density by as much as one order of magnitude.

I3.39
RAMAN AND PHOTOLUMINESCENCE STUDY OF INDIUM NITRIDE FILMS. Jih Shang Hwang, Yang Fang Chen, National Taiwan Univ, Dept of Physics, Taipei, TAIWAN; Fuh Hsiang Yang, Ying Jay Yang, National Taiwan Univ, Institute of Electrical Engineering, Taipei, TAIWAN; Chien Ting Wu, Kuei Hsien Chen, Academia Sinica, Institue of Atomic and Molecular Sciences, Taipei, TAIWAN; Tzong Han Li, Luu Gen Hwa, Fu Jen Catholic Univ, Dept of Physics, Taipei, TAIWAN; Li Chyong Chen, National Taiwan Univ, Center for Condensed Matter Sciences, Taipei, TAIWAN.

Indium nitride (InN) is a promising III-V semiconductor for visible optoelectronics, solar cells and high-speed electronics. However, still few studies have been reported on the photoluminescence (PL) property of InN for the difficulties in attaining high quality samples. In addition, the strong PL emission bands (around 698nm) due to the Cr^{3+} impurity ions in sapphire substrates when a high power laser is used further hamper the PL measurement. In this report, we carefully study the relation between the Raman and PL spectra of epitaxial InN films grown at various substrate temperatures. By precisely controlling the substrate temperatures, we have successfully grown InN films epitaxially on sapphire substrates in a resistive heated MOCVD system. Raman and PL spectra as well as the x-ray rocking curve measurement were employed to characterize the deposited films. A correlation between the Raman linewidth and the PL intensity of the samples deposited at various temperatures was concluded. An explanation based on the TEM microstructure evidence is presented in this paper.

I3.40
INFLUENCE OF MISCUT DIRECTION IN GaN FILM GROWTH ON VICINAL SiC(0001) BY MOLECULAR BEAM EPITAXY. C.D. Lee, Ashutosh Sagar and R. Feenstra, Carnegie Mellon Univ, Dept of Physics, Pittsburgh, PA; O. Shigiltchoff, R.P. Devaty and W.J. Choyke, Univ of Pittsburgh, Dept of Physics and Astronomy, Pittsburgh, PA.

Gallium nitride films on vicinal SiC(0001) substrates with $(1\bar{1}00)$ and $(11\bar{2}0)$ miscut directions were investigated. To eliminate polish damage we have performed hydrogen etching of the SiC substrates. The morphology of GaN films on both off-axis substrates shows similar behavior as those of the etched substrates. The $(1\bar{1}00)$ miscut substrate shows well aligned straight step edges but the $(11\bar{2}0)$ miscut substrates have chevron shaped steps as seen in atomic force microscopy. For the GaN growth, on on-axis substrate, we find that the width of the x-ray rocking curve for the $(10\bar{1}2)$ reflection exhibits a distinct minimum for relatively low Ga/N flux ratios of $\sim$1.1 and the threading dislocation density is $<10^9$ cm^{-2}. Correlated with this minimum the surface morphology is somewhat rough, with a peak and valley topography. In our regular condition with high Ga/N ratio (1.3 - 1.5) and moderate substrate temperature ($\sim$750°C), the film shows smooth morphology but high dislocation density ($>10^{10}$ cm^{-2}). The GaN films on both off-axis SiC substrates grown with high Ga/N flux ratio show a narrow width of the $(10\bar{1}2)$ reflection which is comparable to those of films grown on on-axis substrates using low Ga/N flux ratio. Based on these experimental results we find that GaN film growth on vicinal substrates can be used to achieve smooth morphology as well as minimizing dislocation density.

I3.41
Abstract Withdrawn.

I3.42
INVESTIGATION OF THE OPTIMUM GROWTH CONDITIONS OF WIDE-BANDGAP InAlGaN QUARTERNARY FOR UV-LEDs. T. Yamabi[a,b], A. Kinoshita[a,b], H. Hirayama[a], M. Ainoya[a,b], A. Hirata[b], Y. Aoyagi[a]; [a]The Institute of Physical and Chemical Research (RIKEN), Saitama, JAPAN; [b]Dept of Chemical Engineering, Waseda Univ, Tokyo, JAPAN.

The optimum growth condition of InAlGaN quaternary was carefully investigated grown by metal-organic vapor-phase-epitaxy (MOVPE), in order to obtain room temperature (R.T.) intense ultraviolet (UV) emission of 300 nm-range. InAlGaN quaternary is very attractive for the realization of 300 nm-band UV laser diodes (LDs) and bright light emitting diodes (LEDs), because both room temperature intense UV emission and hole conductivity can be obtained using wide bandgap InAlGaN, due to In segregation effects. We have already achieved 300-340nm intense photoluminescence (PL) from InAlGaN/InAlGaN quantum wells (QWs) at R.T. and also obtained hole conductivity for wide-bandgap (more than 3.8 eV) InAlGaN. In this report, we carefully investigated the optimum growth temperature for various Al and In compositions of $In_xAl_yGa_{1-x-y}N$ quaternary, in order to obtain efficient emission. Samples were grown at 76 torr on the Si -face of on-axis SiC substrates by a conventional horizontal-type MOVPE system. The layer structure is consisting of a 300 nm-thick $Al_{0.18}Ga_{0.82}N$ buffer layer directly grown on SiC substrate and 85 nm-thick InAlGaN layer. Photoluminescence (PL) of each sample were measured excited with Ar-SHG (257 nm) laser. We found that the optimum growth temperature of InAlGaN for intense PL is strongly depending on the Al composition. The optimum growth temperature of InAlGaN were 800 and 760 and 720°C for Al / In content approximately 50 / 2%, 40 / 5% and 18 / 5%, respectively. The PL peak wavelength for each cases were 315, 330 and 370 nm, respectively. The strongest emission was obtained for the InAlGaN with PL peak of 333 nm with the growth temperature of 760°C. From these results, InAlGaN quaternary is very attractive for the use as 300-340 nm-range UV-emitting devices.

I3.43
PREPARATION OF $ZnAl_2O_4$ PSEUDO SUBSTRATES AND GROWTH OF GaN FILMS ON $ZnAl_2O_4$. Z.X. Bi, R. Zhang, W.P. Li, X.S. Wang, S.L. Gu, B. Shen, Y. Shi, Z.G. Liu, Y.D. Zheng, National Laboratory of Solid State Microstructures and Department of Physics, Nanjing University, Nanjing, CHINA.

In this work we studied the growth kinetics of $ZnAl_2O_4$ with the precursor of ZnO/α-Al_2O_3 film structures. ZnO films were deposited on α-Al_2O_3 substrates with pulsed laser deposition (PLD) and then we synthesized $ZnAl_2O_4/\alpha$-Al_2O_3 samples by heating ZnO/α-Al_2O_3 between 900° and 1100° under the flowing O_2 environment. From Auger electron spectroscopy (AES) of $ZnAl_2O_4$ grown under the temperature of 900°, the reaction between ZnO and α-Al_2O_3 is a process of counter-diffusion of Zn_2 and Al_3 which is different from that of one-way diffusion of Zn_2 between ZnO and Al_2O_3 powders. Furthermore, the as-obtained $ZnAl_2O_4$ is not stoichiometrical which leads to the decomposition of $ZnAl_2O_4$ under higher temperature annealing. According to X-ray fluorescence (XFS) measurements of Zn atoms, the apparent growth activation energy of $ZnAl_2O_4$ is determined to be 252kJ/mol. Scanning electron microscope (SEM) images indicate that the morphology of $ZnAl_2O_4$ surfaces changes from the islands to the bulgy-line structures with the increasing of growth time and the corresponding X-ray diffraction (XRD) spectra show that in this transformation process, there exists a stage in which the orientation of $ZnAl_2O_4$ grains is highly disordered. One-step growth of GaN by MOCVD was first developed on thin $ZnAl_2O_4$-coated sapphire substrates, which could be proposed possibly as an alternative way to avoid the annoying low-temperature nitride buffer layer in the MOCVD deposition of GaN. Moreover, purely (0001)-oriented GaN films were grown on the thin $ZnAl_2O_4$-coated sapphire substrate with one-step MOCVD deposition. Excellent structure were also confirmed by PL spectra and PLE spectra.

I3.44
ELECTROLUMINESCENCE AND PHOTOLUMINESCENCE STUDIES OF NITRIDE-RICH $GaN_{1-x}P_x$ SQW STRUCTURE LED GROWN BY LASER-ASSISTED METAL-ORGANIC CHEMICAL VAPOR DEPOSITION. Junjiroh Kikawa, Seikoh Yoshida and Yoshiteru Itoh, Yokohama R&D Laboratories, The Furukawa Electric Co., Ltd., Yokohama, JAPAN.

A nitride rich $GaN_{1-x}P_x$ is very attractive for a light-emitting diode (LED) with a wider visible wavelength due to gigantic band-gap bowing. In this paper, we report on the LED properties of $GaN_{1-x}P_x$ single quantum well (SQW) structure grown by a laser-assisted metal-organic chemical vapor deposition (LA-MOCVD). The sample structure is an Si doped $GaN/GaN_{1-x}P_x$ SQW/Mg doped GaN on the sapphire (0001) substrate. The composition fraction x is estimated to be 0.005-0.01 by using both photoluminescence(PL) peak shift and band bowing parameter 9.31eV. We fabricated the LED using a dry etching technique. The I-V curve and external quantum efficiency of $GaN_{1-x}P_x$ LED was measured. The ideality factor n shows that minority carrier injection of p-n junction of this LED is rather tunneling effect than diffusion one. The electroluminescence (EL) of $GaN_{1-x}P_x$ LED was measured. The EL spectra of LED comprised roughly two peaks; one is strong clear peak located at around 3 eV and the other is a broad weak peak located at around 2.1 eV. We also observed the EL spectra of LED at temperature range from 5K to RT in order to compare with PL spectra of same temperature range. Strong peak of EL spectra has a temperature dependence as same as P_N related peak of PL spectra. Furthermore this strong peak has blue shift of increasing injection current. Based on the these results, two main peaks of EL spectra are considered to be the P of N site (P_N) related iso-electronic hole trap and the yellow band of $GaN_{1-x}P_x$, respectively. This means P_N is similar to In of InGaN, which is efficiency path of electron and hole radiative recombination.

I3.45

GROWTH AND POLARITY OF GaN SINGLE CRYSTALS SYNTHESIZED BY THE Na-FLUX METHOD. Masahiko Shimada, Masato Aoki, Hisanori Yamane, Tohoku Univ, IMRAM, Sendai, JAPAN; Takashi Kajiwara, Tohoku Univ, Dept Chemistry, Sendai, JAPAN; Seiji Sarayama, Ricoh Company, Ltd., R&D Group, Natori, JAPAN; Francis J. DiSalvo, Cornell Univ, Dept Chemistry and Chemical Biology, Ithaca, NY.

GaN single crystals are synthesized at relatively low temperature (900 - 1100 K) and low N_2 pressure (below 10 MPa) using a Na flux. However, the relation between the growth temperature and lower limit of N_2 pressure for crystal growth was not clarified. In the present study, we investigated the temperature and N_2 pressure region to form GaN crystals. We also report the influence of the growth conditions on the crystal morphology. The polarity of the GaN single crystals with a hexagonal wurtzite-type structure was determined using X-ray anomalous dispersion. Ga metal and Na metal were weighed and placed in a BN crucible. This loaded crucible was set in a stainless-steel container. Both steps are carried out in an Ar filled glove box. The sample was heated at 973 - 1123 K and 1 - 5 MPa of N_2 for 200 h. GaN crystals were obtained at lower growth temperatures and/or higher N_2 pressures than the conditions of 1123 K and 1.5 MPa of N_2, or at 1073 K and 1 MPa of N_2. The morphology of GaN single crystals depended on the growth temperature and N_2 pressure. Hexagonal platelet crystals were obtained at lower temperature and higher N_2 pressure, and hexagonal prismatic crystals grew at higher temperature and lower N_2 pressure. Colorless transparent prismatic single crystals with a size of 1.0 x 0.5 x 0.5 mm^3 were synthesized by raising growth temperature at a rate of 0.5 K / h from 1023 to 1073 K under 3 MPa of N_2. The correlation between morphology and polarity was investigated for GaN single crystals synthesized at 1023 K and a constant N_2 pressure of 5 MPa. In the platelet crystals, the smooth mirror surface was (000-1) N-face and the surface with many step edges and hexagonal pits was (0001) Ga-face. The prismatic crystals with smooth surfaces have N-polarity and grew in the -c direction, while the crystals with rough surfaces have Ga-polarity and grew in the +c direction.

I3.46

OPTICAL PROPERTIES OF SUBMICRON WAVEGUIDES BASED ON AlGaN/GaN QUANTUM-WELLS. Tom Oder, Jingyu Lin and Hongxing Jiang, Dept of Physics, Kansas State University, Manhattan, KS.

Submicron waveguide structures based on AlGaN/GaN multiple-quantum wells (MQW) have been successfully fabricated using electron-beam lithography and inductively coupled plasma (ICP) dry etching. The waveguides were patterned with fixed width of 0.5 μm and orientations varying from -30° to 60° relative to the a-axis of GaN. Photoluminescence (PL) emission spectra and dynamic properties of light propagation in these structures were studied by picosecond time-resolved PL spectroscopy. The peak position and line-width of the emission peak were found to vary systematically with orientations of the waveguides and followed the six-fold symmetry of wurtzite structure. This is most likely related to the anisotropy of the exciton/carrier diffusion coefficient along the different crystal orientations in quasi one-dimensional case. We also observed a remarkable decrease in the PL intensity as well as increase in time delay of the temporal response as the location of the laser excitation spot on the waveguides was varied. This can be understood in terms of the properties of polaritons in the waveguides. From the time delay of the temporal response, it has been determined that the speed of generated polaritons, with energy corresponding to the well transitions in the waveguides, is approximately $1.26 \pm 0.16 \times 10^7$ m/sec. The implications of these results to waveguiding in optical devices based on the group III-nitride semiconductors are discussed.

I3.47

IMPLANTATION-PRODUCED LATTICE DAMAGE IN III-NITRIDES. S.O. Kucheyev, J.S. Williams, C. Jagadish, The Australian National University, Dept of Electronic Materials Engineering, RSPhysSE, Canberra, ACT, AUSTRALIA; J. Zou, Univ. of Sydney, Australian Key Center for Microscopy and Microanalysis, NSW, AUSTRALIA; G. Li, Ledex Corporation, Kaohsiung County, Taiwan, REPUBLIC OF CHINA; S.J. Pearton, Univ. of Florida, Dept of Materials Science and Engineering, Gainesville, FL; M.O. Manasreh, Univ. of New Mexico, Dept of Electrical and Computer Engineering, Albuquerque, NM; Y. Nakagawa, Nichia Chemical Industries, Anan, Tokushima, JAPAN.

In the fabrication of III-nitride-based devices, ion implantation represents a very attractive processing tool for several technological steps such as selective-area doping, dry etching, and electrical isolation. However, lattice disorder is always a concomitant (and often undesirable) effect of ion bombardment. Recent studies of ion-beam-damage processes in GaN [1] have revealed that, unlike the situation for mature semiconductors such as Si and GaAs, GaN exhibits a range of intriguing behavior involving extreme property changes under ion bombardment. In this presentation, we discuss implantation-produced damage in wurtzite $In_xGa_{1-x}N$ (with $x \leq 0.2$) and $Al_xGa_{1-x}N$ (with $x \leq 0.6$) films studied by a combination of Rutherford backscattering/channeling (RBS/C) spectrometry, cross-sectional transmission electron microscopy (XTEM), and atomic force microscopy (AFM). Interestingly, results show that an increase in In concentration strongly suppresses dynamic annealing processes (i.e., defect migration and interaction processes) and, hence, enhances the buildup of stable lattice disorder in InGaN under ion bombardment. In contrast, an increase in Al content dramatically increases dynamic annealing in AlGaN films. A comparison of the damage buildup behavior and defect microstructure in InGaN and AlGaN with those in GaN is presented. Results of this study may have significant technological implications for estimation and control of implantation-produced damage in AlGaN/GaN and InGaN/GaN heterostructures. [1] See, for example, a review by S.O. Kucheyev, J.S. Williams, and S.J. Pearton, Mater. Sci. Eng., R **33**, 51 (2001).

I3.48

NEW BUFFER LAYER TECHNIQUE USING UNDERLYING EPITAXIAL AlN FILMS FOR HIGH-QUALITY GaN GROWTH. Tomohiko Shibata[a,b], Yoshihiro Kida[a], Hideto Miyake[a], Kazumasa Hiramatsu[a], Keiichiro Asai[b], Teruyo Nagai[b], Shigeaki Sumiya[b], Mitsuhiro Tanaka[b] and Osamu Oda[b]; [a]Mie Univ., [b]NGK Insulators, Ltd., Mie, JAPAN.

III-V nitride materials are one of the most promising materials for optical devices, such as LEDs, LDs and photodetectors, because of their wide bandgap. It is important to obtain high-quality III-V nitride epitaxial films by optimizing an initial growth stage condition such as a buffer layer in order to obtain high-performance devices. Since there is no suitable substrate that matches with GaN, epitaxy of GaN were mainly employed on sapphire using low-temperature buffer layers using GaN or AlN. Although progress in growth techniques, (0004) X-ray rocking curve (XRC) FWHM value is larger than 200arcsec due to a large number of threading dislocation of the order of 10^8-10^{10} cm^{-2}. In this study, we realized a high-quality GaN epitaxial film by using a high-quality AlN film as the substrate. We characterized the crystal quality by X-ray diffraction, atomic force microscope (AFM) and transmission electron microscope (TEM). At first, 1μm-thickness atomically flat C-plane AlN, with (0002) XRC FWHM value of 50arcsec, was grown on C-plane sapphire substrate by a low-pressure metal organic vapor phase epitaxy (LP-MOVPE) method. Then, 4μm-thickness C-plane GaN was grown on the AlN/sapphire substrate. The obtained GaN films are atomically flat and their typical XRC value of (0004) GaN is less than 80arcsec. From TEM results, it is observed that most of the dislocations in AlN are drastically reduced near the interface between GaN and AlN. Compressive stress at an initial GaN growth stage, which is caused by larger lattice parameter of GaN than that of AlN, is considered to play an important role for dislocation reduction.

I3.49

Abstract Withdrawn.

I3.50

FORMATION OF UNIFORM InN NANOPARTICLES FROM THIN In FILM. Wei-Dong Yang[a,b], Pei-Nan Wang[b] and K.W. Cheah[a]; [a]Department of Physics and Center for Surface Analysis and

Research, Hong Kong Baptist University, Kowloon Tong, HONG KONG; [b]State Key Joint Laboratory for Materials Modification by Triple Beams, Department of Optical Science and Engineering, Fudan University, Shanghai, PR CHINA.

Using a 'two-steps methods', we successfully produced uniform InN nanoparticles from thin In metal film. The first step is to evaporate metal thin film onto the substrate. The second step is nitridation of the metal film in atomic nitrogen rich plasma generated by high-voltage direct-current pulse discharge. InN nanoparticle films were deposited on silicon, quartz and graphite at room temperature, respectively. The X-ray photoelectron spectroscopy measurement showed that only In-N was formed in the samples and the composition of particles was close to stoichiometry. The particle size of the InN films with a rather well defined range of 5-9nm was determined by Atomic Force Microscope (AFM). The image from AFM shows uniform two-dimensional array of InN nanoparticles was formed. Photoluminescence of the InN film showed clear band gap enlargement as a function of the particle size dimension. The peak wavelength has blue shift from 656 nm of the bulk InN to 506.0 nm of nano-InN. Hence, the result shows that using this simple approach, uniform arrays of metal nitride nanoparticles can be fabricated.

I3.51
REMOVAL OF 6H-SiC SUBSTRATE INFLUENCE WHEN EVALUATING GaN THIN FILM PROPERTIES VIA X-RAY. E.A. Preble, P. Miraglia, A.M. Roskowski, S. Einfeldt, and R.F. Davis, North Carolina State University, Department of Materials Science and Engineering, Raleigh, NC.

The three-dimensional microstructure formed during growth in on-axis 6H-SiC(0001) boules consists of multiple domains with varying degrees of tilt. This microstructure is mimicked by subsequently deposited AlN and GaN films to the extent that it is difficult to separate the effects of growth parameters on film substructure from the effects of the underlying SiC in x-ray measurements. Results from x-ray rocking curve mapping studies will be presented that demonstrate both the effects of the SiC substrates on the GaN films and methods to correct for these effects to obtain exclusive and meaningful data regarding the properties of the films. Specifically, the full width half maxima (FWHM) of the rocking curves of the GaN thin films tracked essentially 1:1 with the values of the underlying SiC when the SiC FWHM was greater than ~200 arcsec. Plotting the FWHM with respect to the SiC substrate as well as a variable of importance, such as buffer layer modifications, yielded meaningful and reliable data regarding the films relative to plotting the data for the variable alone. Increasing GaN film thickness is shown to reduce the dislocation population in both screw and edge dislocation types. On-axis GaN (00.2) FWHM values decreased from 269 arcsec to 145 arcsec and off-axis GaN (20.1) FWHM values decreased from 704 arcsec to 359 arcsec for 0.5μm thick and 2.5μm thick GaN films respectively. Additionally, AlGaN buffer layers also helped in reducing the dislocation content of 1μm thick GaN films when compared to standard AlN buffer layers. On-axis FWHM values decreased from 286 arcsec to 146 arcsec and off-axis (30.2) FWHM values decreased from 789 arcsec to 584 arcsec for AlN and AlGaN buffer layers respectively.

I3.52
FORMATION OF GaN SELF-ORGANIZED NANO-TIPS BY NANO-MASKING EFFECT. Harumasa Yoshida, Tatsuhiro Urushido, Hideto Miyake and Kazumasa Hiramatsu, Mie Univ, Dept of Electrical and Electronic Engineering, Mie, JAPAN.

The fabrication of gallium nitride fine tip or pillar structure becomes important technology in the applications of stress-free epitaxy, cold cathode field emitters and quantum dots. We describe a novel method and its mechanism of self-organized tip structure of GaN by using reactive ion etching (RIE). An n-GaN layer grown on a (0001) sapphire substrate by MOVPE was placed on a quartz tray that was put on the cathode electrode. The reactive ion etching was carried out using chlorine plasma generated by 13.56MHz RF power. Numerous tip-shaped GaN pillars (nano-tip structure) with a density of approximately 8×10^9 cm^{-2} were formed after etching. The nano-tips exhibit diameter of several 10 nm and length of about 0.7 μm. It was reported that similar structure formed by photo-electrochemical wet etching seemed to be associated with threading dislocations [1]. However, the nano-tip structure depends on a direction of ion injection in our experiment using a tilted sample. This phenomenon suggests that the nano-tip formation is attributed to a nanometer-scale mask with slower etch rate than GaN. A calculative simulation was carried out under two assumptions that (1) the surface of GaN would be masked by SiO_2 spattered from quartz substrate by Cl^+ ion of plasma, and (2) the positively ionized SiO_2 in the plasma would concentrate to upper part of the tip because of higher electric field. The structure that calculated by this model was well similar to the actual nano-tip structure. These results suggest that the self-organized nano-tip structure is formed by a masking effect of ionized SiO_2 in reactive ion etching using chlorine plasma.

[1] C. Youtsey, L.T. Romano and I. Adesida: Appl. Phys. Lett. 73 (1998) 797.

I3.53
Abstract Withdrawn.

I3.54
LATERAL GROWTH OF InN ON SAPPHIRE. Fuh-Hsiang Yang, Ying-Jay Yang, National Taiwan Univ, Dept of Electrical Engineering, Taipei, TAIWAN; Jih-Hsien Hwang, Chung-Han Lee, Kuei-Hsien Chen, Institute of Atomic and Molecular Sciences, Academia Sinica, Taipei, TAIWAN.

InN with a direct bandgap of about 1.9 eV is highly desirable for optoelectronic and microelectronic applications. It is predicted that InN exhibits the most pronounced transient electron transport characteristics among the III-nitride semiconductors, even a better performance than GaAs and GaN for heterojunction field effect transistors. However, unlike the intensively studied GaN and Ga-rich InGaN, InN has drawn less attention due to restricted growth conditions resulting from the low dissociation temperature of InN and the lack of suitable substrate. InN film grown on sapphire, GaN, etc. had suffered from large lattice-mismatch and tends to form columnar structure due to the large strain built in the interface and thus has inferior quality. In this study, we reported the lateral growth of high quality InN on the stripe-patterned sapphire substrate with an OMVPE system. Trimethylindium and ammonia were used as precursors. The growth temperature ranged between 500-550°C. Silicon dioxide was used as mask and various ratios of mask and opening were used to study the effect of strain on the epitaxial films. The surface morphology and structural properties were investigated. Epitaxial films were achieved due to the greatly reduced strain by lateral growth. X-ray rocking curve with FWHM of 700 arcsec shows the good quality of the film and E2 mode of Raman spectrum with FWHM of 3.5 cm^{-1} is among the best results ever reported in the literature.

I3.55
MICRO-RAMAN SCATTERING FROM HEXAGONAL GaN, AlN, AND $Al_xGa_{1-x}N$ GROWN ON (111) ORIENTED SILICON: STRESS MAPPING OF CRACKS. C. Ramkumar, T. Prokofyeva, M. Seon, and M. Holtz, Dept of Physics and NanoTech Center, Texas Tech University, Lubbock, TX; K. Choi, J. Yun, S.A. Nikishin, and H. Temkin, Dept of Electrical Engineering and NanoTech Center, Texas Tech University, Lubbock, TX.

We report post-growth micro-Raman stress mapping of cracks in GaN, AlN and $Al_xGA_{1-x}N$ grown on (111) oriented silicon. Cracks with an average spacing of $\approx$ 100 μm are observed. These cracks are categorized into two types. The first type of crack propagates through the epilayer, and several microns deep into the substrate and is observed in all the samples investigated. The second type cracks epilayer only and is observed only in GaN. The micro-Raman stress mapping of the first type of crack shows that the epilayers are under biaxial tensile (< 0) stress and the silicon substrate is under compressive (> 0) stress far away from the cracks. The stress in the epilayers as well the substrate is found to relax from the equilibrium (far away from the cracks) values of -0.5 GPa (AlN), -0.16 GPa (GaN), -0.6 GPa ($Al_xGA_{1-x}N$) and 0.36 GPa (Si) as the crack position is approached. Partial relaxation is observed to occur over a range of 10 μm. At the crack position, the epilayers and the substrate are relaxed to nearly stress-free values. The stress mapping of the second type of crack reveals that the substrate is completely relaxed (stress is close to zero) far away from the cracks. At the crack position the GaN epilayer is partially relaxed from -0.2 GPa to -0.08 GPa while the silicon substrate is seen to be under tensile stress of -0.39 GPa. The stress map of epilayers is well described by the distributed force model for both type of cracks. Furthermore, the calculated stress profiles of cracked and uncracked substrate using the above mentioned model are in excellent agreement with the experimental data.

I3.56
Abstract Withdrawn.

I3.57
DIFFRACTION FROM DEFECTED SURFACES: APPLICATION TO GaN(0001). B. Benjaminsson, B. Cui, I.P. Steinke, and P.I. Cohen, Department of Electrical and Computer Engineering and Department of Chemical Engineering and Materials Science, University of Minnesota, Minneapolis, MN.

We have measured the diffraction from rough and smooth GaN(0001) surfaces to serve as a reference for subsequent growth data. For smooth surfaces we have determined the inner potential required to fit the envelope of the allowed oblique Kikuchi lines. Surface wave resonances were observed to enhance integral order and fractional

order beams, but at different off-symmetry angles. At low angles the specular beam was sharp, exhibiting surface wave resonance enhancement off symmetry, corresponding to unrefracted angles. These measurements are compared to dynamical calculations. At higher incident angles the specular beam was split into several components. On rough surfaces, bulk diffraction patterns were observed, with structure factor forbidden beams apparent at particular incident azimuths. The strength of RHEED intensity oscillations was measured at the resonant enhancements, for both specular and nonspecular diffracted beams. Taken together, a standard picture of the diffraction from GaN(0001) is established.

SESSION I4: LIGHT EMITTERS

Chair: Shigefusa F. Chichibu
Tuesday Morning, November 27, 2001
Room 302 (Hynes)

8:30 AM *I4.1
400-nm BAND AlGaInN-BASED HIGH POWER LASER DIODES.
Takeharu Asano, Tsuyoshi Tojyo, Motonobu Takeya, Shinro Ikeda, Takashi Mizuno, Tomonori Hino, Satoru Kijima, Shiro Uchida and Masao Ikeda, Sony Shiroishi Semiconductor Inc., Development Center, Miyagi, JAPAN.

We have successfully improved the productivity and reliability of 400-nm band AlGaInN-based high power laser diodes (LDs) which were suitable for the light sources of high-density optical storage systems. The laser structures were grown on a 3-inch diameter sapphire substrate. The uniformity of thickness and the distribution of photoluminescence wavelength over the 3-inch substrate were within ±5% and ±2.5 nm, respectively. Epitaxial lateral overgrowth (ELO) technique was employed to attain a low dislocation density below 1×10^6 cm^{-2}. Thickness of the ELO-GaN layer was maintained approximately 5 μm to suppress the wafer bending, while the width of the wing region, a half width of the laterally grown region, was extended over 6 μm. So, the laser stripe could be aligned reproducibly into the low-dislocation region of the ELO-GaN. Estimated lifetimes of LDs have exceeded 6000 hours under 30 mW operation at 60°C. We have also investigated the reduction of the aspect ratio and the improvement of laser kink level. A new layer structure was adopted around the active layer, and the optical confinement factor was carefully designed to obtain a narrower beam divergence angle perpendicular to the junction plane ($\theta\perp$), keeping the threshold current (I_{th}) low. In an optimized structure, I_{th} was kept 33 mA and $\theta\perp$ was reduced to 22°. A novel ridge structure suppressing the first-order mode was applied to realize a high kink level maintaining a wide beam divergence angle parallel to the junction plane ($\theta//$). In addition to the novel ridge structure, a narrow ridge width down to 1.5 μm was also effective to obtain a high kink level. As a result, stable transverse mode operation with an output power up to 100 mW was realized at $\theta//$ of 9°, leading to the aspect ratio down to 2.44.

9:00 AM I4.2
HIGHER EFFICIENCY InGaN LASER DIODES WITH AN IMPROVED QUANTUM WELL CAPPING CONFIGURATION.
Monica Hansen, P. Morgan Pattison, James S. Speck, Shuji Nakamura, Steven P. DenBaars, University of California, Santa Barbara, CA.

A thin AlGaN cap is typically employed in InGaN-based lasers and light-emitting diodes (LEDs) to prevent electron overflow from the active region, and to protect the InGaN active region from the high temperature growth of subsequent p-type layers. Electrons that overflow from the active region are lost to nonradiative recombination, which will reduce the efficiency of these devices. For laser diodes this is a more severe problem because of the high current operation. Electrons can overflow the active region into the p-type separate confinement heterostructure (SCH) and cladding layers where they can recombine with majority holes or nonradiatively at dislocation sites, which reduces the internal quantum efficiency of the laser. The placement of this cap can significantly affect the efficiency and operating characteristics of laser diodes. A 200 Å low temperature $Al_{0.2}Ga_{0.8}N$:Mg was placed above the last barrier of a three quantum well (QW) laser diode, as well as directly above the last QW. Lasers with the cap above the last QW exhibit a lower threshold current and a higher efficiency than lasers with the cap above the last barrier. The internal quantum efficiency nearly doubles from 16.6% for lasers with the cap above the last barrier to 34.7% for the cap above the last QW. When the last barrier is present, the electrons pile up at the last barrier and are lost to nonradiative recombination at dislocation sites since the nonradiative lifetime is shorter than the radiative lifetime. Moving the cap to the last QW decrease the nonradiative recombination by dropping the electrons into the QW allowing them to participate in radiative recombination. The reduction in threshold current density is accomplished by either keeping the electrons away from the dislocations with the cap on the last QW, or by simply reducing the dislocation density with lateral epitaxial overgrowth.

9:15 AM I4.3
DEFECTS CREATED BY 25 keV HYDROGEN IMPLANTATION IN n-TYPE GaN.
F.D. Auret[a], W.E. Meyer[a], S.A. Goodman[a], B. Beaumont[b] and P. Gibart[b]; [a]Physics Department, University of Pretoria, Pretoria, SOUTH AFRICA; [b]CRHEA-CNRS, Valbonne, FRANCE.

The defects introduced by 25 keV hydrogen implantation of ELO-MOCVD grown n-GaN were studied using deep level transient spectroscopy (DLTS). This implantation introduces a complex set of defects in GaN, of which most are different to the defects observed after high-energy (MeV) electron and proton implantation. At least three of the defects exhibit a metastable character in that they can be reproducibly removed and re-introduced during reverse and zero bias anneal cycles, respectively. Two of the metastable defects have defect peaks very close together, hindering their accurate characterisation. These two defects can be removed under zero bias annealing at temperatures of between 80 and 100 K and reintroduced during reverse bias annealing in the temperature range 90 to 130 K. In this contribution we discuss possible models for the nature of the defects as deduced from their transformation kinetics.

9:30 AM I4.4
QUATERNARY AlInGaN MQWS FOR ULTRAVIOLET LEDS.
J.P. Zhang, J.W. Yang, V. Adivarahan, H.M. Wang, Q. Fareed, E. Kuokstis, Chitnis M. Shatalov, G. Simin, M. Asif Khan, Dept. of Electrical Engineering, University of South Carolina, Columbia, SC; R. Gaska, M.S. Shur, Sensor Electronic Technology, Inc., Latham, NY.

Ultraviolet light sources are a key requirement for solid-state white lighting and remote chemical sensing systems. In past, several groups have demonstrated UV LEDs with peak emission wavelength around 350 nm using AlGaN/AlGaN multiple quantum well (MQW) in the active region. To overcome fundamental problem of low emission efficiency of AlGaN/AlGaN MQWs due to spontaneous / piezoelectric polarization fields we have explored a novel pulsed atomic layer epitaxy (PALE) technique for the growth of high quality quaternary AlInGaN layers. This technique allows a precise control of layer composition and thicknesses as the growth is carried out by repeats of a unit cell. The PALE approach allows us to grow III-nitrides with high quality at temperatures about 200-300°C lower than those required for conventional metalorganic chemical vapor deposition (MOCVD). This increases In-incorporation in alloys with high Al-mole fractions, which in turn greatly improves surface morphology, structural and interface quality and the optical characteristics. In this paper, we report on a detailed study of the PALE grown AlInGaN single layers and MQWs on sapphire and SiC substrates. The structures were characterized using photoluminescence (PL), X-ray diffraction (XRD) mapping and atomic force microscopy (AFM). PALE grown AlInGaN MQWs exhibited strong satellite peaks even up to the fifth order. Unlike conventional AlGaN layers the PALE grown AlInGaN layers do not exhibit the decrease in PL intensity with increase of Al fraction. The PL data allowed us to estimate the value of the piezoelectric field and the photo induced carrier densities responsible for the screening of this field. We also demonstrate the feasibility of fabricating UV LEDs with peak emission at 340 nm using PALE deposited quaternary AlInGaN MQWs in the active region.

9:45 AM I4.5
COMPOSITION CONTROL DURING GROWTH OF AlGaN CLADDING LAYERS FOR InGaN-MQW LASERS WITH RIDGE FORMED BY SELECTIVE RE-GROWTH (RiS-TYPE LASERS).
Akitaka Kimura, Masaru Kuramoto, A. Atsushi Yamaguchi, NEC Corporation, Photonic and Wireless Devices Research Laboratories, Ibaraki, JAPAN.

We have developed novel InGaN-MQW lasers with selectively grown ridge structures. These RiS (Ridge by Selective re-growth)-type lasers have excellent lateral-mode controllability and can be mass-produced, because the thickness and width defining the ridge can be precisely controlled by photolithography and growth time. To fabricate RiS-lasers, p-AlGaN cladding layers are grown selectively by MOVPE. It is important to control the Al composition of the cladding layers, because the optical confinement and the electrical property are sensitive to it. In the selective growth of alloy materials, the composition is generally affected by the mask pattern. Such a phenomenon may also occur in nitride semiconductors. In this paper, we investigate the mask-pattern-dependence of the Al composition in AlGaN selective growth and propose a simple model to explain the dependency quantitatively. The Al compositions were measured for various mask patterns along the GaN $< 1-100 >$ direction with different mask and window widths by spatially resolved photoluminescence spectroscopy. It was observed that the composition strongly depends on both the window width and the mask width.

While the Al composition was 0.063 in sufficiently wide windows, it decreased with increasing mask width and it also decreased with decreasing window width. It became as low as 0.030 in narrow (2 um) windows with wide (30 um) masks. To explain these results, we supposed a model in which the Al is deposited as polycrystals everywhere on the mask and the Ga is concentrated into the window because of the local loading effect. This model predicts that the Al composition of the selectively grown layers should be inversely proportional to the growth rate. This prediction agreed quite well with the experimental results. Accordingly, the Al composition can be easily estimated from the growth rate. Therefore, we can use this model to control the composition of p-AlGaN layers for RiS-lasers.

10:30 AM I4.6
AMPLIFIED SPONTANEOUS EMISSION FROM InGaN-BASED RESONANT CAVITY LIGHT-EMITTING DIODES. Tal Margalith, P. Morgan Pattison, Phil R. Tavernier, Aimin Xing, David R. Clarke, Evelyn L. Hu, Shuji Nakamura, Steve P. DenBaars, Larry A. Coldren, Depts of Materials and Electrical and Computer Engineering, UC Santa Barbara, CA; Oded Buchinsky, Cypotics Ltd, Karmiel, ISRAEL.

Since their introduction, the demand for GaN light emitting diodes (LEDs) has skyrocketed for applications in lighting and displays. For many of these applications, the directionality and low cost provided by resonant cavity LEDs (RCLEDs) and the yet unrealized GaN vertical cavity laser (VCSEL) are attractive. We discuss our latest RCLED results in particular, the demonstration of amplified spontaneous emission (ASE). The epitaxial structure was grown by MOCVD on a sapphire substrate and consisted of 5μm GaN:Si, ten 4 nm $In_{0.1}GaN$ wells divided by 8 nm $In_{0.03}GaN$:Si barriers, a 20 nm $Al_{0.2}GaN$ electron-barrier layer, and 500 nm of GaN:Mg. The devices were fabricated using a two top contacts scheme, with indium tin oxide (ITO) as the transparent p-contact. The ITO was deposited by DC magnetron sputtering in an oxygen ambient, then annealed at 500°C for 3 minutes to achieve transparency. An 11.5 period Ta_2O_5/SiO_2 dielectric mirror (R>99.5%) was deposited at 250°C on the contacted side, followed by flip-chip bonding of the devices onto an AlN submount. The sapphire substrate was then removed via laser-assisted debonding. Finally, the now-upturned GaN:Si was polished and a second 11.5 period DBR was deposited to form a 6μm thick cavity. The devices were tested at room temperature using both pulsed and continuous current injection. Light versus current characteristics showed an increase in slope past ~30kA/cm^2, indicative of ASE. CW spectrum showed narrow (1 nm) cavity modes spaced approximately 4 nm apart. The devices operated at wavelengths ranging from 390 to 415 nm. The cavity Q was calculated to be about 400. This work was supported by the UCSB Solid State Lighting and Display Center and by the ONR (Colin Wood).

10:45 AM I4.7
LIGHT EMITTERS FABRICATED ON BULK GaN SUBSTRATES. CHALLENGES AND ACHIEVEMENTS. Piotr Perlin, M. Leszczynski, P. Prystawko, P. Wisniewski, L. Dmowski, S. Lepkowski, T. Suski, I. Grzegory, S. Porowski.

During last ten years we have witnessed tremendous development of nitride device technology. The mainstream of this technology relies on GaN/InGaN/AlGaN epitaxy on foreign substrates like sapphire or SiC. In spite of high sophistication of modern growth techniques on sapphire or SiC (since lateral overgrowth methods have been introduced) it is very difficult to lower the concentration of extended defects below 106 cm-2 and to reduce harmful strain fluctuations. For certain device application, like laser diodes for instance, this situation is hardly acceptable. Homoepitaxial growth of GaN and InGaN/AlGaN quantum structure offers a possibility of fabricating dislocations free devices. In this paper we describe the progress made by us in device fabrications (LED and laser structures) on high-pressure, high-temperature grown bulk crystals of GaN. We demonstrate that homoepitaxially grown devices can be characterized by the same quality as that of the substrate no additional dislocation or cracking. Electrical and optical parameters of MQW InGAN/GaN LEDs converge to these of their heteroepitaxial counterparts. Laser structures of perfect structural quality have been fabricated too and they are now being extensively tested (though no current injection lasing has been so far achieved). The quality of fabricated devices, being obviously a reflection of substrate ideality, depends also strongly on the GaN substrate surface preparation and on the chosen growth polarity. We would briefly address these problems in the present work.

11:00 AM I4.8
BRIGHT, CRACK-FREE 300x300 μm^2 InGaN LIGHT EMITTERS ON Si(111). A. Dadgar, M. Poschenrieder, J. Bläsing, T. Riemann, A. Diez, J. Christen, and A. Krost, Otto-von-Guericke-Universitaet Magdeburg, Fakultaet fuer Naturwissenschaften, Magdeburg, GERMANY.

Si substrate is very interesting for the low cost production of GaN based devices and integration with Si electronics. Due to the large thermal mismatch MOCVD grown GaN layers on Si usually crack when exceeding a thickness of 1 μm. By using patterned substrates and overgrowing the open, unmasked regions we could grow thick (>3 μm) GaN light emitter structures on low-temperature AlN seed layers on Si(111) by MOCVD. The diodes show well visible luminescence already suited for low power signalling applications. A detailed investigation by scanning electron microscopy, cathodoluminescence and micro-electroluminescence clearly shows the impact of mask orientation to the growth of side facets and impurity incorporation. Also the amount of growth enhancement of the diode structure resulting in a strong increase in thickness on the edges is dependent on the mask orientation.

11:15 AM I4.9
LOW-TEMPERATURE GROWTH OF RARE-EARTH-DOPED GaN LUMINESCENT THIN FILMS. D.S. Lee, A.J. Steckl, University of Cincinnati, Nanoelectronics Laboratory, Cincinnati, OH.

Rare-earth (RE)-doped GaN has been shown to be an extremely versatile optoelectronic material, with light emission throughout the visible spectrum and at important near-infrared wavelengths. GaN thin films are usually grown at relatively high temperature such as 1000 - 1100°C for CVD and 600 - 800°C for MBE. The standard process for RE-doped GaN is MBE growth at temperatures of 600 to 800°C. In this paper, we show that optically active GaN:RE films can be grown at surprisingly low temperatures. This development has positive applications for the fabrication of electroluminescent devices with relatively low cost deposition methods and on low cost substrate. We report on visible and infrared (IR) emission from GaN:RE thin films grown at 50 - 100°C. We have achieved the characteristic visible and infrared rare earth 4f-4f emission from GaN:RE electro-luminescent devices (ELDs) doped with all RE combinations and growth temperatures investigated, including the growth at 50°C. For example, green emission at 537 nm and 558 nm from GaN:Er ELD had a measured brightness of ~450 cd/m^2 at 50 V bias. X-ray diffraction (XRD) showed that the low-temperature-grown GaN:Er structure ranged from amorphous to weakly polycrystalline. Scanning electron microscopy (SEM) and atomic force microscopy (AFM) indicated that the films had a rough surface and a structure consisting of small grains. The GaN:RE properties, such as crystallinity, photoluminescence (PL) and electroluminescence (EL) intensity were significantly improved with post-growth annealing. For example, an optimum annealing temperature of 800°C was found for room temperature grown GaN:Er films. After anneal, the green emission brightness efficiency increased by approximately an order of magnitude.

11:30 AM I4.10
FABRICATION OF P-N JUNCTION WITH Mg-DOPED WIDE BAND GAP InAlGaN FOR APPLICATION TO UV-EMITTERS. T. Yamanaka[a,b], H. Hirayama[a], A. Kinoshita[a,b], K. Hiraoka[a,b], A. Hirata[b], Y. Aoyagi[a]; [a]The Institute of Physical and Chemical Research (RIKEN), Saitama, JAPAN; [b]Dept of Chemical Engineering, Waseda Univ, Tokyo, JAPAN.

Wide band gap p-type AlGaN has been necessary to realize the UV emitters and the AlGaN based electronic devices. However it is difficult to fabricate p-type AlGaN crystal with over 30% of Al components. We confirmed that p-type InAlGaN crystal could be obtained with wide band gap. In this report, we fabricated p-n diodes with Mg-doped p-type layer with band gap of 3.8 eV, and measured their I-V properties. The diode samples were grown at 76 Torr on the Si-face of on-axis SiC (0001) substrates by a metal organic vapor phase epitaxy (MOVPE). The structure consists of a 100nm-thick Si-doped $Al_{0.18}Ga_{0.82}N$ buffer layer grown on the substrate, 600nm-thick n- $Al_{0.18}Ga_{0.82}N$ layer and Mg-doped $In_{0.05}Al_{0.34}Ga_{0.61}N$ layer. The growth temperature of the Si-doped AlGaN buffer layer, the AlGaN n-type layer, the InAlGaN p-type layer were 1040°C, 1100°C and 750°C, respectively. After the growth, the diode samples were annealed at 750°C under flowing nitrogen (760 Torr) to activate the Mg acceptors. Ni/Au was used for the p, n-type electrode. The I-V properties of the diode samples were measured at room temperature. The working voltage was varied from -10 V to 8 V. The rise voltage of the I-V curve of 3.8 V was agreed with the band gap energy of the InAlGaN crystal measured from the photoluminescence property. On the other hand, no break down was observed through out the whole range of the working voltage. This represented that we succeeded to obtain a high quality p-type InAlGaN film, and indicate that Mg-doped InAlGaN would be a significant material that realize low resistively with wide band gap p-type crystal.

11:45 AM I4.11
ENHANCED PERFORMANCE OF GaN LIGHT-EMITTING DIODES TRANSFERRED TO SILICON BY LASER LIFT-OFF

AND Pd-In BONDING. Z.S. Luo, Y. Cho, V. Loryuenyong, T. Sands, Department of Materials Science & Engineering, University of California, Berkeley, Berkeley, CA; N.W. Cheung, Department of Electrical Engineering and Computer Sciences, University of California, Berkeley, Berkeley, CA; M.C. Yoo, Oriol Incorporated, Santa Clara, CA.

The intimate integration of GaN heterostructures with silicon electronics would enable microsystems that combine the information processing and control functions of CMOS electronics with the light-emitting capabilities of GaN. Furthermore, the replacement of sapphire - the conventional growth substrate for GaN - with silicon, improves heat extraction from the active region of the GaN-based devices, and eliminates the ESD problems associated with the insulating sapphire substrate. Damage-free separation of GaN thin films from sapphire substrate and successful integration of GaN thin film with Si substrate have been demonstrated using laser lift-off transfer in our group. In the present study, we report the successful integration of GaN LEDs onto Si substrates using excimer laser lift-off to transfer LED heterostructures to a temporary receptor substrate, followed by reactive ion etch of buffer layer, Pd-In transient-liquid-phase bonding to silicon, and then release of the temporary receptor. This transfer method results in a bonded LED heterostructure with the same orientation (p-side up) after transfer as before. Such a layer transfer approach enables a top and backside contact metallization scheme which reduces device series resistance, current crowding, and top electrode coverage area. The two-level metallization scheme also allows flexible interconnect routing for future system integration of LED arrays onto various substrates. Enhancement of the performance of the transferred LEDs was found in terms of the threshold voltage (at 20mA) and diode ideality factor. The threshold voltage and the diode ideality factor for the transferred diodes are 3.3V and 2.4, respectively, significantly improved from 4.3V and 4.8 before transfer. Both improvements can be attributed to the reduction of device series resistance due to the improved contact scheme. Furthermore, both diodes can withstand a reverse bias up to -30V without breakdown, indicating the LLO and bonding steps do not introduce crystalline defects. (Support from NSF (DMI-0088145) is gratefully acknowledged.)

SESSION I5: NITRIDE ALLOYS AND LATERAL EPITAXY

Chair: Henning Riechert
Tuesday Afternoon, November 27, 2001
Room 302 (Hynes)

1:30 PM *I5.1
THEORY OF ELECTRONIC STRUCTURE EVOLUTION IN GaAsN AND GaPN ALLOYS. Alex Zunger and P.R.C. Kent, National Renewable Energy Laboratory, Golden, CO.

Using the empirical pseudopotential method and large atomistically relaxed supercells we have systematically studied the evolution of the electronic structure of GaPN and GaAsN, from the dilute nitrogen impurity regime to the nascent nitride alloy. We show how substitutional nitrogen forms Perturbed Host States (PHS) inside the conduction band whereas small nitrogen aggregates from localized Cluster States (CS) in the band gap. By following the evolution of these states and the "perturbed host states" with increasing nitrogen composition, we propose a new model for low nitrogen content GaAsN and GaPN alloys. As the nitrogen composition increases, the energy of the CS is pinned while the energy of the PHS plunges down as the nitrogen composition increases. Strongly localized wave functions, low-pressure coefficients, and sharp emission lines from the CS characterize the impurity limit (PHS above CS). We do not find support to the formation of impurity bands, as the CS-CS interaction is much weaker than the PHS-CS interaction. The *amalgamation limit* (PHS overtake the CS) is characterized by a coexistence of localized states (leading to high effective mass, exciton localization, Stoke's shift in emission vs. absorption) overlapping delocalized PHS (leading to asymmetrically broadened states, low temperature coefficient, delocalized E_+ band at higher energies). The *alloy limit* (PHS well below CS) may not have reach experimentally, but is predicted to be characterized by conventional extended states. Our theory shows that these alloy systems require a polymorphous description, permitting the coexistence of many different local environments, rather than an isomorphous model that focuses on few impurity-host motifs.

2:00 PM I5.2
DEEP STATES IN UNDOPED InGaAsN DETECTED BY PHOTOLUMINESCENCE AND PHOTOCONDUCTIVITY. Gh. Dumitras, Infineon Technologies, GERMANY; A. Yu. Egorov, Ioffe Institute, St. Petersburg, RUSSIA; H. Riechert, Infineon Technologies, GERMANY.

We use photoluminescence (PL), spectrally resolved photoconductivity and photoconductivity response time measurements to reveal the existence of deep traps in InGaAsN samples. The samples were grown by molecular beam epitaxy (MBE) using a RF N-source, without intentional doping. Both strained InGaAsN quantum wells (QW) and thick (300nm) layers lattice-matched to GaAs were studied. In all samples the N-content is between 1 and 2%. The process of thermal annealing dramatically reduces the concentration of the deep traps, simultaneously with increasing and blue-shifting the PL from the InGaAsN region. PL measurements show sub-bandgap emission, easily saturated by increasing the excitation light intensity. Above 0.7eV the PL shows distinct peaks, some of which disappear after annealing. Photoconductivity spectra measured at 77K show small electrical resistance in as-grown samples for photon energies below the bandgaps of the substrate and the InGaAsN. After annealing, the photoconductivity spectra are dramatically changed. Temperature-dependent photoconductivity response-time measurements were used to determine the activation energies of the deep traps. These are in good agreement with the positions of the peaks observed in sub-bandgap PL. Finally, results for similar InGaAs and InGaAsN samples will be compared.

2:15 PM I5.3
STUDY OF THE LOCAL ENVIRONMENT OF NITROGEN IN InGaAsN LAYERS. H. Ch. Alt, FHM - Munich University of Applied Sciences, Dept of Engineering Physics, München, GERMANY; A. Yu. Egorov, H. Riechert, Infineon Technologies, Corporate Research Photonics, München, GERMANY; J.D. Meyer, B. Wiedemann, University of Frankfurt, Institute for Nuclear Physics, Frankfurt, GERMANY.

The alloy system $InyGa_{1-y}As_{1-x}N_x$ recently attracted much interest as a promising material for lasers of high efficiency and high temperature stability in the 1.3-micrometer wavelength region. The addition of a small amount of nitrogen to GaAs ($x < 0.03$) during epitaxial growth leads to a remarkable shrinkage of the fundamental gap. The characterization of the N containing layers is usually done by indirect methods, such as x-ray diffraction (XRD) or photoluminescence (PL). In this study, two methods are presented which are sensitive to the incorporation of N in the crystalline lattice itself. $InyGa_{1-y}As_{1-x}N_x$ quantum well structures ($x < 0.03$, $y < 0.4$) were grown by solid source molecular beam epitaxy (MBE) using a radio-frequency-coupled plasma source to generate reactive nitrogen from N2. It is shown by Fourier transform infrared absorption spectroscopy (FTIR) that the local mode at 471 cm^{-1} which is due to the isolated N defect can be used as a quantitative tool to assess the substitutional nitrogen fraction. Most interesting, no shift or splitting of the local mode is observed in InGaAsN layers compared to GaAsN layers. This is interpreted as evidence that N in these layers bonds to Ga atoms only. Implantation of N into bulk InAs crystals supports this model. Thick GaAsN layers grown under similar conditions were also investigated by nuclear reaction analysis (NRA) under channeling conditions. The normalized yield of the 14N(d,a)12C nuclear reaction was measured as a function of the angle of incidence. The deuteron energy was 1.4 MeV. Using a kinematical model for the reaction between deuterons and nitrogen atoms, the area projection of the N concentration in the GaAs lattice was calculated. N is predominantly localized on string positions. However, the half width of the distribution is larger than the thermal oscillation amplitude of the matrix atoms (FWHM of the area density approximately 0.08 nm). The fraction of nitrogen atoms on interstitial sites is estimated to be less than 5%.

2:30 PM I5.4
RAMAN STUDIES OF GaNP ALLOY. I.A. Buyanova, W.M. Chen, Linkoping University, Dept of Physics and Measurement Technology, Linkoping, SWEDEN; E.M. Goldys, Macquarie University, Division of Information and Communication Sciences, Sydney, AUSTRALIA; H.P. Xin, C.W. Tu, University of California at San Diego, Department of Electrical and Computer Engineering, La Jolla, CA.

The strong effect of nitrogen on the electronic properties of the GaNP alloy is caused, among other effects, by a large difference in the lattice constant and stiffness between GaN and GaP. As a consequence, local atomic relaxation, large non-uniformity of local strain as well as long-range ordering are predicted for the alloy. Detailed information about structural properties of the alloy systems, including lattice imperfection, strain and compositional uniformity, can be obtained by using Raman scattering (RS) spectroscopy. We employed this technique to characterize the effect of nitrogen on the structural properties of the GaNP alloy with nitrogen content up to 3%. All investigated GaNP thick epilayers were grown by gas-source molecular-beam epitaxy (GS MBE) on (100) GaP substrates. According to the XRC measurements samples with a low (<1%) nitrogen content are coherently strained, whereas partial strain relaxation occurs at a higher N concentration. The two-mode behavior of the alloy is clearly shown. The frequency of the GaP-like LO

phonons is found to decrease with N composition as -1.13 $cm^{-1}/x(\%)$. This dependence can be largely attributed to the biaxial strain in the GaNP epilayers, due to a lattice mismatch with the GaP substrate. The frequency of the GaN-like optical phonons is found to be more sensitive to the nitrogen composition and increases by 2.6 $cm^{-1}/x(\%)$. The addition of nitrogen also causes a dramatic quenching of the two-phonon Raman scattering and the appearance of the zone edge GaP-like vibrations. We attribute these effects to the local distortion of the GaNP lattice induced by nitrogen, as well as possible clustering of the N atoms.

3:15 PM *I5.5
EPITAXIAL LATERAL OVERGROWTH OF GaN. Bernard Beaumont, Philippe Vennéguès, Pierre Gibart, CRHEA–CNRS, Valbonne, FRANCE.

Numerous defects, mainly threading dislocations (TDs), are generated in the heteroepitaxy of GaN on sapphire or 6H-SiC. The Epitaxial Lateral Overgrowth (ELO) technology consists in masking parts of the highly dislocated starting GaN with a dielectric mask; then opening stripes with given oriented directions and finally restarting the growth. At the beginning of the regrowth, deposition occurs only in the openings of the mask. No deposition is observed on the mask, which corresponds to Selective Area Epitaxy (SAE). Then, after filling the openings and due to growth anisotropy, TDs are prevented from propagating in the overlayer by the dielectric mask, whereas GaN growing from the opening (coherent growth) keeps the same TDs density than the template at least at the earliest stages of the process. Actually, two main ELO technologies exist; the simplest one involves a single growth step after stripe opening. In this one-step-ELO (1S-ELO), growth in the opening remains in registry with the GaN template underneath (coherent part), whereas GaN over the mask extends laterally (wings). This leads to two qualities of GaN; highly dislocated above the opening, but low dislocation densities over the masks. Using this technique, devices have to be grown on the wings. Conversely, in the first step the of a two-step-ELO (2S-ELO) process, the growth conditions are controlled in a way to get triangular stripes. Inside these stripes, threading dislocations arising from the templates are bent at 90° when they encounter the inclined lateral facet. In the second step, the growth conditions are modified to get full coalescence. In this two-step-ELO, only the coalescence boundaries are defective. In depth characterisation of ELO GaN reveals that the intermediate stages of the process induce inhomogeneities in impurities incorporation and in stress distribution. However, the ELO technology produces high quality GaN with TDs densities in the mid $10^{6}cm^{-2}$, linewidths < 1 meV of the low temperature photoluminescence (PL) near band gap recombination peak and deep electron traps reduced below $10^{14}cm^{-3}$ (compared to mid $10^{15}cm^{-3}$ in standard GaN).

3:45 PM I5.6
THE INFLUENCE OF MASK STRIPE MISORIENTATION ON THE MORPHOLOGY AND WING TILT OF LATERALLY OVERGROWN GaN. Michael D. Craven, Paul T. Fini, Steven P. DenBaars, James S. Speck, Shuji Nakamura, Materials Department, University of California, Santa Barbara, CA.

Lateral epitaxial overgrowth (LEO) is a well-known means of reducing threading dislocation densities in heteroepitaxial GaN films. Basic LEO involves masking a GaN layer with a dielectric film that has periodic, parallel stripe openings (windows) and regrowing GaN via metalorganic chemical vapor deposition (MOCVD). The GaN grows vertically through the openings in the dielectric mask and laterally over the mask until adjacent LEO 'stripes' coalesce to form a planar film. Throughout our studies of LEO GaN, we have observed a variety of stripe morphologies and degrees of crystallographic wing tilt for mask stripes nominally aligned to $<1\bar{1}00>_{GaN}$. The experiments reported herein define a significant source of inconsistencies in the structure of LEO GaN. The precise LEO mask stripe orientation has been shown to have a pronounced effect on the morphological and structural characteristics of the overgrown GaN. The characteristics of LEO stripes grown with mask orientations that deviate up to 6° from $<1\bar{1}00>_{GaN}$ were studied. LEO stripes grown through an SiO_2 mask (5 μm windows, 20 μm period) oriented 'exactly' parallel to $<1\bar{1}00>_{GaN}$ were, under certain conditions (1100°C growth temperature and 76 Torr), rectangular in cross section with stable vertical $\{11\bar{2}0\}$ facets. Misorienting the mask relative to $<1\bar{1}00>_{GaN}$ by only 1° increased the width-to-height ratio of the stripes by 24%, thereby increasing the crystallographic wing tilt from 0.75° to 0.83°, confirming a well-established trend. Inclined sidewall facets appeared at 2° misorientation and became dominant at larger misorientations, which can be explained in terms of atomic step density on the stripe sidewalls. Crystallographic wing tilt monotonically increased with mask stripe misalignment (from 0.75° to 2.29° for misorientations of 0° to 6°) independent of stripe morphology. Lastly, the effects of mask stripe orientation on stripe-stripe coalescence will be discussed and a model explaining these effects will be proposed. This research proves the importance of crystallographically accurate mask stripe alignment for consistent and reproducible lateral epitaxy of GaN.

4:00 PM I5.7
SUPERIOR STRUCTURAL QUALITY OF NEWLY DEVELOPED GaN PENDEO-EPITAXIAL LAYERS. Zuzanna Liliental-Weber, Lawrence Berkeley National Laboratory, Berkeley, CA; David Cherns, H.H. Wills Physics Laboratory, University of Bristol, Bristol, UNITED KINGDOM; Robert Davis, Department of Materials Science and Engineering, University of North Carolina, Raleigh, NC.

Pendeo-epitaxial layers grown on SiC with AlN buffer layer and Si_3N_4 caps studied in the past appeared to show some advantages compared to epitaxial laterally overgrown layers. However, two "meeting fronts" were formed in the pendeo layers: one where side walls of pendeo were grown together and the second where two side walls grown over Si_3N_4 caps were joining. The structural quality of this second "meeting front" was usually lower than the first one. In the newly developed GaN pendeo layers Si_3N_4 cap was not applied. TEM studies show superior quality of such layers where only first "meeting front" was formed replacing the second one by homo-epitaxial growth. This approach lead to a high quality of the first "meeting front" where tilt/twist measured by Large Angle Convergent Beam Electron Diffraction (LACBED) was almost negligible and a number of dislocations formed in homo-epitaxial parts was substantially reduced. Our earlier studies showed that tilt/twist across the "meeting front" leads to the formation of additional half-loops in the overgrown areas, therefore, reducing tilt/twist leads to lower defect density and higher uniformity of the layers. The structural quality of the newly developed pendeo-layers will be compared to epitaxial laterally overgrown layers.

4:15 PM I5.8
A NOVEL DISLOCATION FILTERING TECHNIQUE FOR EPITAXIAL GROWTHS OF GaN. Joon-Yeon Chang, HanSu Kim, HyungJun Kim, Dawei Zheng, and Ya-Hong Xie, University of California Los Angeles, Dept of Materials Science and Engineering, Los Angeles, CA; J.C. Chen, Kopin Corporation, Taunton, MA.

High dislocation density is the characteristic feature of the state-of-the-art GaN epitaxial films due to the lacking of lattice matched substrates. While this feature does not prevent epitaxial GaN to be used for LED applications, it does significantly limit the performance of transistors and the lifetime of lasers. A novel technique for filtering dislocations is applied to epitaxial growths of GaN on sapphire (0001). The key feature of our approach is dislocation blocking using amorphous films. The word blocking has dual meanings: Firstly, it means stopping dislocation half loops from expanding along the hetero-interface in the in-plane directions. Secondly, it means the blockage of threading dislocations from propagating through the epilayer along the wafer surface norm. Dislocation blocking is achieved through masking of the substrate surface prior to the single epitaxial growth step. The basic concept carries certain similarity to the dislocation necking used in bulk crystal growths. Cross-sectional transimission electron micrographs show that the very high density of dislocations threading along the surface norm above the hetero-epitaxial interface is completely blocked by the mask. A fraction of dislocations made a 90-degree bend into the direction parallel to the wafer surface, which are then blocked by the masking structure. The dislocation density in the film grown over the mask is reduced to below 10^{7} /cm^{2}. There is no dislocation visible within the TEM field of view encompassing approximately 15.6 μm^2 of the surface area. Comparing to the well-known PENDEO or ELOG techniques, our approach employs only one epitaxial growth step of GaN, provides complete filtering of dislocations from the area near the mask edges, and reduces the highly defective area due to the lateral growth front coalescence by a factor of 2.

4:30 PM I5.9
HIGH QUALITY ELO GaN ON PATTERNED SILICON(111) SUBSTRATES MICRO-CHARACTERIZED BY SPECTRALLY RESOLVED SCANNING CATHODOLUMINESCENCE MICROSCOPY. T. Riemann, J. Christen, A. Krost, Inst of Experimental Physics, Otto-von-Guericke-Univ Magdeburg, GERMANY; A. Strittmatter, L. Reissmann, D. Bimberg, Inst of Solid State Physics, Technical Univ Berlin, GERMANY.

The evolution of almost crack-free, fully coalescent epitaxial lateral overgrowth GaN (ELOG) grown on patterned Silicon substrates using a maskless process [1] is directly imaged by spatially and spectrally resolved scanning cathodoluminescence (CL) microscopy. Prior to the MOCVD growth of the ELO layer, the Si(111) substrate was structured into a periodic pattern of trenches and terraces by photolithography and reactive ion etching. While GaN deposition initially occurs at all planar faces, further growth in the trenches is eventually inhibited and finally suppressed by the lateral extension and subsequent full coalescence of the GaN stripes developing from the terraces. The formation of growth domains with specific structural and optical properties during the evolution of the ELO GaN is

directly imaged by cross-sectional CL mappings: The domain of initial (0001) growth on the terrace tops is characterized by weak and broadened Near Bandedge Emission dominated by Yellow Luminescence and strong donor-acceptor-pair recombination, indicating a high defect density in this area. The vertical extension of threading dislocations throughout the whole domain height is visualized by lines of drastically decreased quantum efficiency, running up to the surface. The onset of facetted lateral expansion, i.e. the transition to the actual ELO GaN, results in an abrupt rise of integral CL intensity and an immensely reduced dislocation density. In this domain we preferentially find sharp excitonic luminescence which shows a further decrease of linewidth with advancing growth, proving the strong improvement of crystal quality. While full strain relaxation is observed at the cleaved sample faces, the homogeneously strained nature of the crack-free ELO GaN is evidenced in large area plan-view CL scans. [1] Strittmatter et al., Appl. Phys. Lett. 78, 727 (2001).

4:45 PM I5.10
CANTILEVER EPITAXY OF LOW DEFECT DENSITY GaN ON SILICON CARBIDE AND SILICON (111) SUBSTRATES.
T. M. Katona, M.D. Craven, P.T. Fini, J.S. Speck, S.P. DenBaars, Electrical and Computer Engineering Department and Materials Department, University of California, Santa Barbara, CA.

Cantilever epitaxy (CE) on both 6H n-type silicon carbide and Si (111) substrates is demonstrated and characterized by scanning electron microscopy, atomic force microscopy, and x-ray diffraction. Cantilever epitaxy employs growth from periodic, parallel mesas, which are formed by etching the substrate. GaN/AlN/Si and GaN/AlN/SiC layers were grown via metalorganic chemical vapor deposition on reactive ion etched substrates. The $<1\bar{1}00>_{GaN}$ oriented stripes are shown to effectively reduce the threading dislocation density of the "wing" regions, the GaN spanning the trenches. Dislocation densities in the seed region are estimated, by the step terminations as seen in atomic force microscopy, to be $\sim 9 \times 10^8$ cm^{-2} on SiC and $\sim 7.5 \times 10^9$ cm^{-2} on Si (111) as opposed to the wing region showing no step terminations. The GaN is of similar quality to that obtained by lateral epitaxial overgrowth (LEO), but requires only one growth step and no mask material. Although no mask/wing interface exists, crystallographic wing tilt is observed in CE GaN. These results demonstrate that wing tilt is not solely due to the mask or mask/wing interaction. Tilt ranging from 0.15° - 0.77° is observed for wings with lateral to vertical aspect ratios (w/h ratios) of 0.12 - 0.41, contrary to previous LEO results predicting tilt below 0.2° for comparable w/h ratios. The tilt is controlled by varying the V/III ratio and by using a two step lateral growth condition. Using this two step approach, tilt is reduced to within the mosaic of the crystal, with the full width at half max ranging from 588 - 804 arcseconds for (0002) rocking curves with the scattering plane perpendicular to the stripe direction. The effect of substrate trench depth on nucleation and subsequent growth will also be presented.

SESSION I6: POSTER SESSION
Tuesday Evening, November 27, 2001
8:00 PM
Exhibition Hall D (Hynes)

I6.1
Abstract Withdrawn.

I6.2
DEFECT PROPERTIES AND BEHAVIOR OF Au IMPLANTS IN GaN.
W. Jiang, W.J. Weber, S. Thevuthasan, Pacific Northwest National Laboratory, Richland, WA.

Epitaxial single-crystal GaN films on sapphire were implanted 60° off the $< 0001 >$ surface normal with Au^+ ions over a range of fluences at low and room temperatures. The disorder on both the Ga and N sublattices at the damage peak is simultaneously studied in situ using non-Rutherford backscattering spectrometry in channeling geometry. Multiple crystallographic axes have been chosen to determine the disordering behavior along different orientations and to define the site location of the Au implants. The relative Ga disorder at the damage peak for the Au^+ implantation at room temperature exhibits four clear stages that consist of gradual disorder accumulation below 1 dpa, a rapid disorder increase between 1 and 6 dpa, a disorder saturation stage between 6 and 20 dpa, and a rapid amorphization process due to the extension of amorphized surface layer at higher doses. Au migration in GaN was observed during both room-temperature implantation and higher-temperature annealing processes. While there is only a slight recovery of defects in Au^+ implanted GaN at 1000 K, Au atoms readily diffuse into the amorphized surface region following thermal annealing at 870 K. At lower damage levels, Au atoms appear to stay near the mean ion-projected-range and may be trapped at defects. Full amorphization was observed at the GaN surface under high-fluence (86.2 Au^+/nm^2) irradiation at room temperature. However, the material still remained partly crystalline in the damage peak region. This behavior is primarily attributed to a high mobility of Ga defects and to simultaneous recovery processes. In addition, the dependence of mean lattice displacement distance on dose, determined from a computer simulation on the experimental angular yield profiles, will also be presented and discussed.

I6.3
IMPACT OF Al(Ga)N INTERLAYERS ON STRESS AND CONDUCTIVITY OF GaN ON Si(111).
A. Reiher, J. Bläsing, M. Poschenrieder, A. Dadgar, P. Veit, A. Diez, F. Bertram, J. Christen, and A. Krost, Otto-von-Guericke-Universitaet Magdeburg, Fakultaet fuer Naturwissenschaften, Magdeburg, GERMANY.

Low temperature (LT) AlN interlayers have been shown by Amano et al. [1] to decrease stress and to improve the layer quality in GaN on sapphire. They can also be used to suppress cracks for the growth of thick AlGaN/GaN Bragg-reflectors as presented recently [2]. Since GaN layers on Si exceeding 1 μm in thickness suffer from thermal tensile stress leading to cracks one possibility to avoid this is to introduce LT AlN-interlayers. However, for device applications like LEDs on Si it is interesting to use the Si-substrate as back contact and interlayers with high Al content might lead to high series resistance. We investigate LT-interlayers doped with Si in their efficiency to suppress cracking and to improve the layer quality as well as their resistivity. First results show that for pure AlN interlayers grown at low and at GaN growth temperatures the effect on crack suppression is nearly the same while this is not the case for lower Al content interlayers. In the case of pure AlN interlayers we find that only for a low growth temperature around 600°C and for the GaN growth temperature x-ray rocking curves are narrowest. Furthermore AFM measurements show that interlayers with high Al content are more efficient in reducing the surface roughness. [1] Hiroshi Amano, Motoaki Iwaya, Takayuki Kashima, Maki Katsuragawa, Isamu Akasaki, Jung Han, Sean Hearne, Jerry A. Floro, Eric Chason, and Jeffrey Figiel, Jpn. J. Appl. Phys. 37, L1540 (1998) [2] K. Waldrip, J. Han, S.J. Hearne, J.J. Figiel, G.A. Petersen, and S.M. Meyers, MRS Fall Meetin Boston, G 12.8 (2000).

I6.4
STUDY OF HIGH NITROGEN COMPOSITION GaNAs MATERIAL QUALITY BY X-RAY DIFFRACTION AND PHOTO-LUMINESCENCE.
T.K. Ng, S.F. Yoon, S.Z. Wang, W.K. Loke, W.J. Fan, School of Electrical and Electronic Engineering, Nanyang Technological University, SINGAPORE.

GaNAs alloy growth is a subject of considerable interest due to its technological importance in long wavelength lasers emitting within the optical-fiber communication wavelength window (1.3 - 1.55 μm) with high temperature performance. We grow the GaNAs materials on a semi-insulating (001) GaAs substrate using a solid source molecular beam epitaxy (SSMBE) system with a RF plasma source. The nitrogen incorporation is achieved by tuning either the nitrogen background pressure or the RF power. The materials are then characterised by X-ray diffraction (XRD) and photoluminescence. Nitrogen compositions varying from 0.1 percent to a record high value of 6 percent are obtained as characterised by XRD. Measurements of the GaNAs layers by XRD suggest that there is little or no phase separation. In addition, for GaAs cap and GaNAs layer structure of 2 nm and 100 nm, respectively, clear Pendelloesung fringes are still observable at a high nitrogen composition of 4.8 percent, indicating efficient nitrogen incorporation in our system and excellent GaNAs material quality. The effect of annealing temperature on the improvement of GaNAs photoluminescence is also studied for the temperature range of 600 and 850°C.

I6.5
THE ELECTRONIC PROPERTIES OF EXTENDED CRYSTAL DEFECTS IN WURTZITE GaN FILM.
Shaoqing Wang, Hengqiang Ye, Shenyang National Laboratory for Materials Science, Institute of Metal Research, Chinese Academy of Sciences, Shenyang, P.R. CHINA.

GaN has attracted much attention for its deep potential of applications in short-wavelength opto-electronics, high-power and high-temperature electronics. Huge amounts of crystal defects compose the unique feature of epitaxial GaN film due to large lattice mismatch between the film and the substrate. Nevertheless, the performance of GaN appliance still far out-reaches the other III-V semiconductors. The puzzle has been investigated heavily both theoretically and experimentally in recent years. Even though, many debates and contradictory opinions are still frequently seen in literatures. Threading dislocations and domain boundaries are the major extended crystal defects in GaN film. The atomic structures of these defects have been largely determined [1,2]. Due to difficulty of calculation, the electronic structures of these defects and their

influences to the GaN band structure are still not well understood. In the present work, we deal the problem by ab initio molecular dynamics simulation and DFT tight-binding calculation. The electronic properties of crystal defects in Wurtzite GaN are studied in detail. The roles of extended crystal defects in GaN optoelectronic devices are explored. [1] S.Q. Wang, C.P. Liu, H.Q. Ye, Mater. Character. 44, 385-389 (2000). [2] S.Q. Wang, Y.M. Wang, H.Q. Ye, Appl. Phys. A70, 4, 475 (2000).

I6.6
IMPROVEMENTS OF STRUCTURAL AND OPTICAL PROPERTIES OF GaN/$Al_{0.10}Ga_{0.90}$ MULTI-QUANTUM WELLS BY ISOELECTRONIC In-DOPING. Lianshan Wang, Soo Jin Chua, Wenhong Sun, Opto-electronic System Cluster, Institute of Materials Research & Engineering, Singapore, SINGAPORE.

The effects of isoelectronic In-doping were studied on the structural and optical properties of 3-periods and 10-periods of GaN/$Al_{0.10}Ga_{0.90}$N multi quantum wells (MQWs). The GaN/$Al_{0.10}Ga_{0.90}$N MQWs were grown on u-GaN/sapphire via metalorganic chemical deposition (MOCVD) at 1050°C in H_2 carrier gas. X-ray diffraction (XRD), transmission electron microscopy (TEM) and micro-Photoluminescence (PL) measurements revealed that In-doping into well layers improves the crystalline and optical properties of MQWs relative to those samples without In-doping. With increasing Trimethylindium (TMIn) flow rates from 4.2 μmol/min to 42.6 μmol/min, PL peaks from well layers obviously redshifted, due to the decrease of the strain along the interfaces between MQWS, irrespective of 3-periods or 10 periods of MQWs. The decrease of the interface strain was also confirmed by the observation of TEM

I6.7
INFRARED AND UV RAMAN SPECTRA OF AlN THIN FILMS GROWN ON Si(111). V.M. Naik, Department of Natural Sciences, University of Michigan-Dearborn, Dearborn, MI; W.H. Weber and D. Uy, Scientific Research Laboratory, Ford Motor Company, Dearborn, MI; Y.V. Danylyuk, G.W. Auner and L. Rimai, Dept. of Electrical and Computer Engineering, Wayne State University, Detroit, MI; D. Haddad, R. Naik, Dept. of Physics, Wayne State University, Detroit, MI.

Infrared (IR) and Raman spectroscopy have been used to study epitaxial AlN thin films (thickness ~200 nm) grown on Si(111). The films were grown by plasma source molecular beam epitaxy at growth temperatures of 400 - 650°C. Reflection high energy electron diffraction, X-ray diffraction and transmission electron microscopy have been used to characterize the microstructure and epitaxial relations in these films. The low temperature (400°C) grown AlN films form an initial amorphous layer followed by c-axis oriented growth whereas the samples grown at higher temperatures (~650°C) show a significantly reduced amorphous region. Raman spectra were obtained using UV excitation (244 nm), which gives a substantial spectral enhancement due to closeness of their energy band gap to the excitation energy (5.01 eV). The Raman active A_1(LO) and E_2, and IR active A_1(TO) and E_1(TO) zone center phonons have been observed in these films. Raman spectra of AlN/Si(111) grown at 650°C yield A_1(TO), E_2, and A_1(LO) modes at ~610, 652 and 884 cm^{-1}, respectively. These are slightly lower than corresponding values reported for bulk AlN, probably because of strain in the films. The Raman and IR spectroscopic results of AlN films grown at 400 and 650°C and their structural dependence will be discussed.

I6.8
STUDIES OF ELECTRONIC STATES IN MODULATION DOPED p-AlGaN/GaN SUPERLATTICES. A.Y. Polyakov, N.B. Smirnov, A.V. Govorkov, Institute of Rare Metals, Moscow, RUSSIA; A.V. Osinsky, P.E. Norris, Corning Applied Technologies, Woburn, MA; S.J. Pearton, Department of Materials Science and Engineering, University of Florida, Gainesville, FL; J. Van Hove, A. Wowchak, P. Chow, SVTA, Inc., Eden Prairie, MN.

Electrical and optical properties of p-AlGaN/GaN modulation doped SLs prepared by MBE were studied by means of conductivity versus temperature, admittance spectroscopy, photoinduced current spectroscopy, microcathodoluminescence (MCL) spectra measurements and measurements of effective diffusion lengths. It is shown that in SLs grown on GaN underlayers the sheet resistivity is about two orders of magnitude lower than for reference p-GaN films and the resistivity of SLs remains lower up to temperatures of about 600K. For SLs grown on AlGaN underlayers the gain in resistivity is much more moderate and certain advantages in using such SLs are envisaged only for temperatures below room temperature. The reason for this lower gain is a considerable decrease in hole mobility compared to p-GaN. The effect is somewhat tentatively attributed to worse crystalline perfection of these SLs. It is also shown that such SLs are characterized by a strongly broadened MCL peak and the presence of additional hole traps with activation energy of about 0.4 eV. Despite that the photosensitivity and MCL intensity of these SLs are much better than for reference p-GaN samples.

I6.9
HIGH MOBILITY NITRIDES. Kenneth Scott Butcher, Trevor Tansley, Macquarie University, Semiconductor Science and Technology Laboratories, Physics Dept, Sydney, AUSTRALIA.

The highest mobility nitrides ever grown were indium nitride thin films produced in these labs 17 years ago. An electron mobility of 2700 $cm^2/V.s$ for a carrier concentration of 5.5x1016 cm^{-3} was achieved [1]. The original reactive ion sputtering unit used to produce those films is still in existence, and has recently been substantially upgraded. In this presentation we describe the parameters that are important for high purity indium nitride film growth, while providing the most recent results for films grown using the upgraded system. [1] T.L. Tansley and C.P. Foley, Electron Lett. 20 (1984) 1066.

I6.10
COMPOSITIONAL AND STRUCTURAL STUDIES OF AMORPHOUS III-N (III = Al, Ga, In) GROWN BY ION-ASSISTED DEPOSITION. Uday Lanke, Annette McIvor, Simon Granville, Joe Trodahl, School of Chemical and Physical Sciences, Victoria University of Wellington, Wellington, NEW ZEALAND; Andreas Markwitz, John Kennedy, Institute of Geological and Nuclear Sciences, Lower Hutt, NEW ZEALAND; Ho Keun Lee, Department of Physics, Kangwon National University, Chunchon, KOREA; Antoine Bittar, Measurement Standards Laboratory, Industrial Research Limited, Lower Hutt, NEW ZEALAND.

Amorphous III-nitride (III = Al, Ga, In) films have been deposited onto various substrates by electron beam evaporation of the group-III metal in the presence of an energetic nitrogen ion beam. The films were deposited at room temperature using nitrogen ion energies in the range 40-900 eV. Raman spectroscopy and x-ray diffraction confirm the amorphous nature of the films and annealing studies establish that the films begin to crystallise at a temperature of about 550°C. Rutherford backscattering spectroscopy and nuclear reaction analysis show that the group-III:N atomic ratio is approximately one for all films. Films grown using a nitrogen ion energy of near 500 eV are transparent across the visible, whereas as the ion energy is lowered below 300 eV the films become progressively more opaque. We suspect that the visible absorption signals the presence of homopolar (e.g. Ga-Ga) bonds in the films produced with low ion energy. We believe that the high density of heteropolar bonds in the best films is the result of energetic nitrogen ions breaking the weaker homopolar bonds as the films grow. To investigate the local bonding environment of the group-III or N atoms, we have measured the extended x-ray absorption fine structure (EXAFS) of the transparent GaN films. The EXAFS results indicate that the films are dominated by heteropolar tetragonal bonding, with a low density of homopolar bonds.

I6.11
CHARACTERIZATION OF GaN AND RELATED MATERIALS USING CHEMICAL IMAGING. F.H. Long, M.P. Nelson, R. Smith, and P.J. Treado, ChemIcon Inc., Pittsburgh, PA; A.J. Ptak and T.H. Myers, Department of Physics, University of West Virginia.

Rapid development of GaN and related compound semiconductors requires new and improved characterization tools. Chemical imaging combines molecular spectroscopy with digital image processing imaging to rapidly provide molecular images.high information content chemical property maps of materials. When applied to semiconductor materials, chemical imaging can rapidly and nondestructively provide information about crystal quality, carrier concentration, strain, chemical and alloy composition. Raman chemical imaging is an example of chemical imaging, where Raman spectra are generated with high spatial resolution (250nm), forming a two or three dimensional compositional or structure map of spectra, a semiconductor substrate or device. Chemical chemometric Chemometric image analysis techniques such as principal component analysis, multivariate analysis, and other sophisticated approaches are used to extract semiconductor property information of relevant to the high dimensionality data often produced in chemical imaging experiments. device fabrication. For example, Raman spectroscopy can be used to measure carrier concentration in GaN films. Using multivariate calibration techniques the accuracy of such measurements can be greatly improved. High accuracy measurement techniques are essential for the statistical improvement of manufacturing processes. Raman chemical imaging of hexagonal regions in HVPE grown GaN films on sapphire has revealed 6-fold symmetric carrier concentration variations near the hexagonal defect. Possible physical explanations for this observation will be discussed. Such characteristic patterns would be difficult if not impossible to find in singlefind with traditional point by point scanning measurements. We will apply such methodologies to the investigation of lateral epitaxial overgrown GaN

films. Using multivariate calibration techniques the accuracy of such measurements can be greatly improved. Chemical imaging results for InGaN multiple quantum wells will also be presented. The photoluminescence from the InGaN active layer is observed to vary on the micron distance scale. We attribute this variation to the mesoscale variation of the local indium concentration. It is generally recognized that indium alloy fluctuations are an important property of InGaN and are critical to the operation of InGaN LEDs.

I6.12
CHARACTERIZATION OF $Al_xGa_{1-x}N/Al_yGa_{1-y}N$ DISTRIBUTED BRAGG REFLECTORS GROWN BY PLASMA ASSISTED MOLECULAR BEAM EPITAXY. H. Klausing, F. Fedler, J. Aderhold, D. Mistele, T. Rotter, J. Stemmer, O. Semchinova and J. Graul, Laboratorium für Informationstechnologie, Universität Hannover, Hannover, GERMANY; S. Günster, Laser Zentrum Hannover e.V., Hannover, GERMANY.

Distributed Bragg Reflectors (DBRs) based on $GaN/Al_xGa_{1-x}N$ have been fabricated and investigated by several groups in order to strengthen the development of vertical cavity surface emitting lasers (VCSELs) and resonant-cavity light emitting diodes for the near UV and visible spectral range. Nevertheless there were only few attempts to realize $Al_xGa_{1-x}N$ based DBRs which are suited to be monolithically integrated in VCSEL structures emitting at wavelengths smaller than 370 nm.
We report on $Al_xGa_{1-x}N/Al_yGa_{1-y}N$ DBRs and superlattices with up to 30 periods grown by r.f. plasma assisted molecular beam epitaxy with the aid of two Al effusion cells. Several samples were grown on sapphire (0001) with an AlN mole fraction varying between $0.3 \leq x \leq 1$ $(0.1 \leq y \leq 0.2)$ at temperatures of up to 890°C. In some samples, an $Al_xGa_{1-x}N$ interlayer was used to reduce cracking of the quarter wave stack and improving surface morphology by choosing the Al content so that strain energy in the DBR structure could be compensated. Surface reconstruction could be observed by in situ reflection high-energy electron diffraction (RHEED) indicating a good surface morphology. Structural investigation was performed by X-ray diffraction (XRD) and scanning electron microscopy (SEM) measurements. Kinematical simulations have been fitted to XRD $\omega/2\theta$-scans. The fit parameters have been refined from $Al_xGa_{1-x}N$ single layers with corresponding AlN mole fraction for each of the quarter wave layers so that quarter wave layer thicknesses and AlN mole fraction could be determined. The cristalline quality and uniform periodicity was indicated by x-ray diffraction rocking curves. The thicknesses of the quarter wave layers have been independently extracted from SEM images, which also show cracks on the μm scale. Room-temperature calibrated reflection and transmission (R&T) measurements were performed using a Perkin Elmer λ900 double beam spectrometer. The experimental data was simulated using the transfer matrix method. The dispersion data, including refractive indices and absorption coefficients, used in the calculation were extracted from R&T measurements being applied on the above mentioned $Al_xGa_{1-x}N$ single layers. Thus the self-absorption of the DBRs is given beyond the reflectivity. The thickness of the quarter wave layers was calculated such that the measured peak reflectances occured from 325 nm to 410 nm.

I6.13
INFLUENCE OF SUBSTRATE ORIENTATION ON PHOTO-LUMINESCENCE IN InGaN/GaN MULTIPLE QUANTUM WELLS. P. Chen S.J. Chua and W. Wang, Institute of Material Research and Engineering, Singapore, SINGAPORE.

InGaN/GaN multiple quantum well (MQW) is the key structure for blue and green light-emitting diodes and laser diodes. Thus, the understanding of optical properties of the structures becomes highly important. It has been known that potential fluctuations, originating from segregation effects in InGaN, is one of important reseans resulting in multiple emission peaks in InGaN/GaN MQW. In this study, the photoluminescence spectra of InGaN/GaN MQW grown on different orientation sapphire substrates at 720°C have been investigated. Four group substrates were used. Their orientations are c-plane, a-plane and c-plane with off-set 2 degree or 6 degree towards a-plane, which indicates the different surface step structures, and the regularest step structure is expected in the last two groups. The optical measurements showed the strong and clear influence of substrate orientation on the photoluminescence in InGaN/GaN MQWs. All InGaN/GaN MQWs grown on c-plane substrates showed the double-peak emission, however, all InGaN/GaN MQWs grown on the others substrates showed the single-peak emission, and the strongest emission was obtained on the substrate of c-plane with off-set 2 degree towards a-plane. Meantime, peak position is moved to long wavelength on the substrates with an off-set angle. The origination of the emissions has also been discussed at different excitation levels. These results indicate that the regular step structure on the sbustrates can seriously affect the growth of InGaN/GaN MQW. Segregation effect in InGaN will lead to the high In composition regions, mostly quantum-wire like structure in the substrates with an off-set angle due to the regular steps on them. It can be concluded that the surface steps on substrates play an importent role in the formation of the In-rich InGaN quantum-wire like structure.

I6.14
FIRST OBSERVATION OF RAMAN SCATTERING IN EPITAXIAL $Al_{1-x}In_xN$ THIN FILMS. D.B. Haddad, R. Naik, Wayne State Univ, Dept of Physics and Astronomy, Detroit, MI; Y.V. Danylyuk, M.J. Lukitsch, G.W. Auner, L. Rimai, Wayne State Univ, Dept of Electrical and Computer Engineering, Detroit, MI; V.M. Naik, University of Michigan-Dearborn, Dept of Natural Sciences Dearborn, MI; W.H. Weber and D. Uy, Scientific Research Laboratory, Ford Motor Company, Dearborn, MI.

We report the first observation of UV and visible near-resonance enhanced Raman scattering in epitaxial wurtzite $Al_{1-x}In_xN$ (0001) $(0 \leq x \leq 1.0)$ thin films. The films (thickness $\sim$150 nm) were grown by Plasma Source Molecular Beam Epitaxy on sapphire (0001) substrates at a low temperature of 375°C. X-ray diffraction measurements confirm the c-plane growth of alloy films. The Raman spectra were obtained using UV and visible excitations with wavelengths of 244 nm and 514.5 nm. A substantial spectral enhancement is seen for Al-rich samples using 244 nm (5.01 eV) radiation due to the closeness of their band gap energy to the excitation energy. On the other hand samples with x $\sim$0.6 (energy band gap $\sim$2.5 eV) show significant enhancement with 514.5 nm (2.41 eV) excitation. The A_1(LO) and E_2 zone center phonons have been observed for all samples. The A_1(LO) phonon frequency shows the expected decrease with increasing x. The E_2 mode shows a two-mode behavior supporting the recent theoretical predictions. Due to increased resonance enhancement, strong second- and third-order spectra are seen in some films.

I6.15
CHARACTERIZATION OF GROUP III NITRIDES WITH GRAZING INCIDENCE-ANGLE X-RAYS. Hiroyuki Takahashi, Jitsuo Ohta, Hiroshi Fujioka, Masaharu Oshima, University of Tokyo, Department of Applied Chemistry, Tokyo, JAPAN; Masao Kimura, Advanced Technology Research Laboratories, Nippon Steel Corporation, Futtsu, JAPAN.

To develop high performance GaN devices, it is necessary to characterize the structural properties of the surface device region precisely. Grazing incidence-angle X-ray diffraction (GIXD) is a powerful technique for this purpose because grazing incidence-angle X-rays penetrate only several hundred angstroms from the sample surfaces due to the total reflection effect. Grazing incidence-angle X-ray reflectivity (GIXR) measurements are also useful because they provide information on the abruptness of the hetero-interfaces without destructive sample preparations. In this presentation, we discuss the structural characteristics of the surfaces and interfaces of group III nitrides grown on various substrates using GIXD and GIXR. AlN and GaN samples used for these experiments were grown by pulsed laser deposition (PLD) at a substrate temperature of about 750°C. GIXD measurements were performed at the synchrotron beam line BL-3A in KEK-PF. The wavelength of the X-ray beam was set at 0.9 Å. We carried out the reciprocal space mappings for in-plane and out-of-plane diffractions from the nitride films at various incidence angles to obtain information on a depth distribution of the lattice constants. X-ray reflectivities were measured by scanning 2θ from 0.4° to 2.5° and the data were analyzed by the recursive application of the Fresnel equation. With GIXD measurements, we have found that there exists a distribution in the lattice constants as a function of depth from the surface. GIXR measurements have revealed that hetero-interfaces between the PLD-grown group III nitride films and substrates are quite abrupt (roughness: 0.5 nm) and that the intermixing of atoms does not occur at the interface between AlN and GaN.

I6.16
TEMPERATURE DEPENDENCE OF FAR INFRARED CHARACTERISTICS OF GaN FILMS WITH DIFFERENT DOPINGS. T.R. Yang, M.M. Dvoynenko, Physics Dept, National Taiwan Normal University, TAIWAN, ROC; Z.C. Feng, Axcel Photonics, Marlborough, MA.

We have studied the temperature dependent infrared (IR) reflectance of Si-doped GaN epitaxial films with different doping levels and thickness deposited on sapphire substrate by metalorganic chemical vapor deposition. The IR measurement was carried out by near normal incidence in the temperature range of 80-300 K, for GaN/sapphire samples with the thickness ranging between 0.5-4 microns and doping levels between 5E16-2E19 per cubic cm. Some opposite characteristics below the main GaN reststrahelen band, i.e. between 350-500 wavenumbers, were observed and these interesting behaviors are explained from theoretical calculation and the phase

change of the interferometric beam. Using the factorized model of the dielectric function, we have deduced out the plasma frequencies and broadening parameters of GaN phonons. The plasma frequencies, obtained at the temperature range of 80-300 K are dependent on the temperature weekly for high doping samples but varied in a different behavior for low doping and un-doped high quality samples. A physical explanation is given from the dependence of the donor binding energy on the donor density, which is from the screening effect of hydrogenic model. The donor binding energy could vanishes for a large carrier concentration which will has a less dependence on temperature. We suggested that this week temperature dependence of plasma frequency for high doping level samples could possibly be due to the high dislocation density in the GaN epi-films. Detailed discussion on IR characteristics of GaN with large range variations of doping levels and thickness is given.

I6.17
HIGH QUALITY CONTINUOUS GaN TEMPLATE GROWN ON CRACKED III-NITRIDES FILMS. Maosheng Hao, Institute of Material Research and Engineering, Singapore, SINGAPORE; Ji Zhang, Eng Kee Sia, Soo Jin Chua, National University of Singapore, Dept of ECE, Singapore, SINGAPORE.

The III-nitrides semiconductor system has progressed in many practical applications very rapidly in the past three decades, though the device quality III-nitrides films are generally grown by hetero-epitaxy technology, such as on sapphire or SiC, due to the lack of its own native substrates. The stress in the III-nitrides films is quite large, and it generally is released by generating dislocations, however it sometimes leads to cracks of the films when the stress is tensile and large beyond a certain critical value. Such cracks often happen in the thick or heavily Si-doped GaN and AlGaN films. We have demonstrated that the continuous GaN film could be grown on the cracked heavily Si-doped GaN film using metalorganic chemical vapor deposition. The SEM observations proved that the surface morphology of the continuous GaN is very good. Moreover, TEM studies showed that the screw dislocation density could be largely reduced in the continuous films, while it seemed that there was no effect on the density of pure edge dislocation in the continuous GaN film. The further studies on the possibilities and properties of growing continuous GaN film on the cracked AlGaN is under investigation. Unlike the cracked GaN, the cracked AlGaN introduces stress in the GaN films grown on it. The effect of such stress is investigated and comparisons of the two methods are made with photoluminescence, X-ray diffraction, SEM and TEM measurements. This continuous GaN films may be used as a template to grow device structures.

I6.18
DARK LINES AND DARK SPOTS IN CATHODOLUMINESCENT IMAGE OF GaN MICROCRYSTALS. Hisashi Kanie, Kose Sugimoto, Hiroaki Okado Science Univ. Tokyo, Dept of Applied Electronics, Chiba, JAPAN.

Microcrystalline GaN based phosphors are developed for an application in a field emission display because of their high conductivity and chemical and thermal stability during device sealing processes. Direct observation of nonradiative centers in microcrystals are crucial point to optimize growth conditions for phosphors with high luminescent efficiency. CL image observation of GaN microcrystals with high lateral resolution ($\lesssim$30 nm) was carried out on a SEM (Topcon DS130S) at 3 kV equipped with a real-time-RGB-separation detector. Most of the CL image was observed in the blue region detected through a dichroic mirror. Bulk GaN microcrystals grown by the nitridation of Ga_2S_3 with NH_3 at 1100°C were observed. Dark spots with a density of $8 \times 10^{+8}$ cm^{-2} were observed on side facets of truncated-pyramidal GaN crystals standing on a basal c plane. The order of dark spot density was comparable to that of the reported threading dislocations in MOCVD grown epitaxial GaN on a sapphire or SiC substrate. Dark lines were observed in a c-plane for crystals grown with a c-axis lying horizontally. The directions of the dark lines were $< 11\bar{2}0 >$ or $< [1\bar{1}00 >$ and the end of the dark line corresponded to a dark spot on a side facet $\{11\bar{2}l\}$ or $\{[1\bar{1}0l\}$. These dark lines correspond to the dislocations in a MOCVD grown GaN films. Dark spots were scarcely observed on a c-plane for all the crystals. The reason of the low density of the dark spots on a c-plane is because the formation of screw dislocation was reduced for the stress free crystals. Observation of high resolution CL image is useful to reduce the density of nonradiative dislocations.

I6.19
PHOTOLUMINESCENCE STUDY OF DEEP-LEVEL DEFECTS IN UNDOPED GaN. M.A. Reshchikov, H. Morkoç, Dept of Electrical Engineering, Virginia Commonwealth University, Richmond, VA; S.S. Park, K.Y. Lee, Samsung Advanced Institute of Technology, Suwon, KOREA; R.J. Molnar, MIT Lincoln Laboratory, Lexington, MA.

Identification of defects responsible for the omnipresent yellow luminescence (YL) in GaN still remains to be a challenging problem. While it seems to be unambiguously proved that this band is related to transitions from the conduction band or a shallow donor to a deep acceptor, it is still not clear if only one or several different acceptors contribute to the broad luminescence band. We studied photoluminescence (PL) and PL excitation (PLE) spectra in a large number of undoped GaN layers grown on sapphire by molecular beam epitaxy (MBE), metal-organic vapor phase epitaxy (MOVPE) and hydride vapor phase epitaxy (HVPE). Some of the HVPE-grown GaN layers with thicknesses of more than 200 μm were separated from the sapphire substrate by laser lift-off and represented bulk freestanding templates of very high quality. The same position and shape of the YL band were reproduced in many samples grown by MBE and MOVPE: maximum at 2.23 eV and the full width at half maximum (FWHM) of about 460 meV. However in some samples the band maximum was observed at about 2.0 eV. In the 10 μm-thick GaN layers grown by HVPE two bands could be resolved: at 1.9 eV and 2.4 eV. The freestanding template revealed a broad band (FWHM=530-680 meV) which position depended on excitation intensity and varied from 2.25 eV to 2.50 eV. PLE spectra taken from various samples represented a broad band with apparent maximum at about 3.3 eV. For below-band-gap excitation, the intensity of the YL band was independent of temperature except for the one in the freestanding template. The latter was temperature independent above 60 K, yet at lower temperatures the PL intensity decreased by 5 times. An activation energy of 15 meV has been determined that is related to a barrier in the adiabatic potential in the excited state of the defect.

I6.20
FINTE-ELEMENT CALCULATION OF STRESS DISTRIBUTIONS IN THICK LAYER AlGaN IN THE PRESENCE OF TRIGONAL MICRO-CRACKS. Q.K.K. Liu, Theoretical Physics Division, Hahn-Meitner-Institute, Berlin, GERMANY; D. Rudloff, T. Riemann, J. Christen, Institute of Experimental Physics, Otto-von-Guericke-University Magdeburg, Magdeburg, GERMANY; M. Diesselberg, S. Einfeldt, D. Hommel, Institute of Solid State Physics, University of Bremen, Bremen, GERMANY; A. Kaschner, A. Hoffmann, C. Thomsen, Institute of Solid State Physics, Technical University Berlin, Berlin, GERMANY.

Motivated by a series of experimental measurements of the three dimensional stress distributions in an AlGaN layer that contains micro-cracks, we have calculated the corresponding stress distributions by the finite-element method. The results confirm the intuitive notion that on the top of the layer in the midst of an area surrounded by micro-cracks, the stress has the quality of a stressed film. Stress relaxation takes place as one moves towards the cracks. Deeper towards the interface with the GaN buffer stress relaxation is hindered as one moves closer to the foot of the cracks. The stress in the GaN buffer has the distinctive characteristic of being compressive underneath the AlGaN layer and tensile in the gap of the cracks. We examine the roles played by the GaN buffer and the orientation of the hexagonal axes. The theoretical results are compared with the position and depth sensitive cathodoluminescence measurements, micro-Raman spectroscopy and x-ray diffraction.

I6.21
COMPUTATION OF ELECTRONIC PROPERTIES OF POINT DEFECTS IN GALLIUM NITRIDE. J.M. Vail, A. Yang, Univ of Manitoba, Dept of Physics and Astronomy, Winnipeg, MB, CANADA; R. Pandey, Michigan Technological Univ, Dept of Physics, Houghton, MI.

Gallium nitride has recently emerged as a semiconducting material with promising applications in high-temperature optoelectronic devices. It is well-known that the lack of native substrates leads to a substantial number of defects in as-grown GaN such as vacancies which are responsible for defect-induced emissions limiting the performance of devices. In this work, we will investigate the optical processes associated with the F center in GaN (i.e. an excess electron bound by a nitrogen vacancy in the lattice) using a computational method that has been widely successful for point defect properties in ionic crystals. The method employs Hartree-Fock based molecular cluster treatment of the defect region with classical shell model embedding. Methodological issues are first addressed, namely effective ionic charges, basis set optimization in the crystal, and equilibration between quantum cluster and classical embedding regions. Atomic-scale localization vs. diffuseness is considered for the optical excitation process. Long-range polarization of the crystal by the positively charged defect is included in applying the Franck-Condon principle for the excitation.

I6.22
COMBINED UV RAMAN SCATTERING AND PHOTO-LUMINESCENCE OF GaN AND RELATED MATERIALS ON SAPPHIRE. Z.C. Feng, Axcel Photonics, Marlborough, MA; M. Kuball, H.H. Wills Physics Lab., Univ of Bristol, UNITED

KINGDOM; K.P.J. Williams, G.D. Pitt, Renishaw plc, Gloucestershire, UNITED KINGDOM.

Micro-Raman scattering and micro-photoluminescence spectroscopy under excitation of ultraviolet (UV) 325 nm from a He-Cd laser have been employed to study GaN and related materials grown on sapphire substrates by low-pressure metalorganic chemical vapor deposition (MOCVD). A variety of GaN thin film materials (un-doped, Si- and Mg-doped) and InGaN/GaN/sapphire structures were investigated. Using a newly designed and developed UV Raman-PL microscope system, combined Raman and PL spectra can been obtained from same runs. A series of interesting results are obtained at room temperature (RT). For n-type GaN films, with increasing the SiH4 flow, RT PL of GaN band edge emission showed first a slight blue-shift first and then a red shift. The bandwidth decreased first and then increased, peak intensities also increased first and then decreased. We have used the bandgap renormalization due to the many-body effects and the potential fluctuations caused by the random distribution of doping atoms to explain these interesting trends. Combined UV RS-PL spectra from p-type GaN were also investigated. PL characteristics from GaN band-to-band and Mg-related transitions are conveniently distinguished. Competition between the Mg-related 2.8-3.2 eV PL bands is revealed with different Mg-doping levels. Multiple Raman LO (up to 5LO) resonant modes are exhibited, which is due to the outgoing resonance with the fundamental GaN band gap. We have also observed extra phonon modes, which may be related to the p-type doped impurities. Similar combined UV RS-PL spectra and resonance enhancement of multiple LO modes from InGaN/GaN/sapphire structures are also obtained. They are varied with the indium composition. These fruitful results demonstrate the capabilities of UV micro-RS-PL technology for the research and development of GaN and other wide bandgap materials.

I6.23
PHOTOLUMINESCENCE DEPTH-PROFILING OF LATTICE-MISMATCHED InGaN THICK FILM ETCHED BY INDUCTIVELY COUPLED Cl_2 PLASMA. Ji-Myon Lee, Yong-Tae Moon, Seong-Ju Park, Kwangju Institute of Science and Technology, Dept of Materials Science and Engineering and Center for Optoelectronic Materials Research, Kwangju, KOREA.

Although the InGaN layer is essential for the purpose of developing optoelectronic devices, the mechanism of light emission in InGaN along with the structural evolution still remains unanswered. In this work, photoluminescence (PL) depth profiling of highly strained $In_{0.1}Ga_{0.9}N$ epitaxial film has been studied by using an inductively coupled Cl_2 plasma etching. The photoluminescence measurements showed that a thick $In_{0.1}Ga_{0.9}N$ layer (0.2 μm) consists of three different structural phases; (i) InN-rich region near the film surface, (ii) defect-free region in the middle of the film, and (iii) strained InGaN region at the bottom of the film. The intensities of PL peaks from InN-rich phases [region (i)] decreased with the increase of etching time. However, the peak at higher wavelength attenuated faster than the other, indicative of different spatial distributions of InN-rich phase. After the removal of surface layer of 500 Å, the PL of InN-rich phase totally disappeared, indicating that the InN-rich phase region is confined within the depth of 500 Å. Furthermore, the PL intensity of sound InGaN [region (ii)] was exponentially decreased as the etch time increases due to the decrease in the film thickness of sound InGaN which are free from the defects, such as the native defects and inclusions. In region (iii), the elastic compressive strain between InGaN and GaN significantly influenced the luminescence property of InGaN, resulting in the blue shift of PL peak energy as the thickness of InGaN layer was decreased. The asymmetric distribution of In along the vertical distribution in the InGaN thick film will be explained in terms of In surface segregation and compositional/compressive stresses.

I6.24
Abstract Withdrawn.

I6.25
Abstract Withdrawn.

I6.26
SCANNING NEAR FIELD ELECTROLUMINESCENCE MICROSCOPY CHARACTERIZATION OF BLUE InGaN/GaN DIODES ON Si SUBSTRATES. D. Rudloff, T. Hempel, J. Christen, A. Dadgar, A. Krost, Otto-von-Guericke-Univ Magdeburg, Inst of Experimental Physics, Magdeburg, GERMANY; A. Alam, M. Heuken, AIXTRON AG, Aachen, GERMANY.

Electroluminescence (EL) is the most significant measure for light-emitting diodes since it probes the relevant properties of the fully proc-essed device under operation. Our EL measurements are performed using a combined scanning near field optical microscope (SNOM) / scanning electron microscope (SEM) setup. The EL is collected with a fiber tip of an atomic force microscope mounted inside a SEM cathodoluminescence setup. The EL is dispersed by a 0.3m spectrometer, and detected by liquid cooled CCD camera. During a detection scan over the area of interest the morphology and a complete EL spectrum are recorded at each pixel and stored. All types of data cross sections through the 4-dimensional data set $I_{EL}(x, y, \lambda)$ are subsequently generated, such as local EL spot spectra $I_{EL}(x_i, y_i, \lambda)$, sets of mono-chromatic EL images $I_{EL}(x, y, \lambda_i)$, EL spectrum line scans $I_{EL}(s(x, y), \lambda)$, as well as EL wavelength im-ages (ELWI) $\lambda_{Peak}(x, y)$, mapping the local emission wavelength. The spectrally and spatially resolved EL (SNOM-EL) allows a direct microscopic correlation of morphological and optical properties of the device. Furthermore, our combined SNOM / SEM setup enables SNOM-EL, SNOM-PL as well as and cathodoluminescence (CL) at the same sample position. The device under investigation is an InGaN/GaN multiple quantum well electroluminescence test structure (ELT) MOVPE grown on Si (111) sub-strate. ELWI's reveal local emission peak wavelengths between 410 and 420 nm and exhibit a blue shift towards the p-contact. The SNOM-EL-characterization is performed as a function of injection current and directly images the lateral injection efficiency. Cross section measurements will be performed to microscopically visualize the vertical current injection through the device.

I6.27
INFLUENCE OF GROWTH TEMPERATURE ON EMISSION EFFICIENCY OF InGaN/GaN MULTIPLE QUANTUM WELLS. Fei Chen, A.N. Cartwright, Paul M. Sweeney, M.C. Cheung, University at Buffalo, Dept of Electrical Engineering, Buffalo, NY; Jeffrey S. Flynn, David Keogh, ATMI Inc, Danbury, CT.

Electron-microscopy and cathodoluminescence of InGaN have demonstrated the existence of nanoscale regions of spatially localized potentials. However, the effects of growth conditions, although acknowledged, remain unclear due to the complex nature of growth processes, defects and piezoelectricity in III-N materials. In this work, we present femtosecond time-resolved and CW photoluminescence spectroscopy to compare emission from MOVPE grown InGaN / GaN MQWs deposited on HVPE GaN/Sapphire at three different growth temperatures but under otherwise identical conditions. The PL linewidth increased and the peak emission energy decreased as the growth temperature was reduced. The sample grown at an intermediate growth temperature exhibited total integrated luminescence intensity, which is 1.8 times and 2.9 times greater than the samples grown at higher and lower growth temperatures respectively. Moreover, consistent with localized electronic states, recombination lifetimes measured at 14 K are energy dependent, increasing as the photon emission energy is decreased. The localized potential needed to fit this dependence increased from 36 meV to 256 meV with decreasing growth temperature consistent with a resulting increase in the depth of the localization energy states. Moreover, although potential minima can result from localized strain relaxation, the observed behavior cannot be completely explained by strain-induced piezoelectricity. Finally, we present a phenomenological carrier recombination dynamics model based on the competition of quantum well-like radiative recombination, localized radiative recombination in potential minima and non-radiative recombination through defects, to provide an explanation of the observed emission dynamics and efficiency. Furthermore, this model is supported by the comparison of emission spectra in these samples, as well as by the transition of the spectra from a single peak emission to a double peak emission in the more efficient MQWs grown under the intermediate growth temperature. A more complete model of these materials requires a continued systematic study of each growth parameter.

I6.28
EXCITONS BOUND TO STRUCTURAL DEFECTS IN GaN. M.A. Reshchikov, D. Huang, F. Yun, H. Morkoç, Dept of Electrical Engineering, Virginia Commonwealth University, Richmond, VA; C.W. Litton, Air Force Research Laboratory, Wright Patterson AFB, OH.

We analyzed the photoluminescence (PL) spectrum of undoped GaN samples grown by molecular beam epitaxy on sapphire substrate. While the PL spectrum from high-quality samples contains peaks related to free excitons and excitons bound to a shallow donor and unidentified acceptor, the spectrum from some samples involves sharp unidentified peaks in the photon energy range of 3.0 - 3.45 eV. The most commonly observed peaks are at 3.20-3.23 (doublet), 3.30, 3.36 and 3.41 eV. Attribution of these peaks to excitons follows from linear and sometimes superlinear increase of their intensity with excitation intensity without saturation up to 100 W/cm^2. With increasing temperature these peaks quench in a fashion similar to excitons bound to shallow donors and acceptors. In order to relate the observed peaks to the structural defects, we performed shallow etching of the surface with hot H_3PO_4 acid or, alternatively, with dissolved KOH at room temperature in the presence of

UV-illumination (photoelectrochemical, or PEC, etching). In the former case the pits were etched at the dislocation sites, while in the latter case the dislocations remained unetched due to a deficit of photogenerated holes at dislocation sites. We established that the 3.41 eV peak disappeared both after PEC and hot wet etching suggesting that the associated defect is at the GaN surface. Peaks at 3.2 and 3.35 eV could be enhanced greatly by PEC etching suggesting that the dislocations can bind excitons. The presence of the peaks related to excitons with large activation energies was correlated with the growth conditions, surface morphology and polarity.

I6.29
NANOBUMPS IN $In_xAl_{1-x}N$ SYSTEMS: A NEW KIND OF QUANTUM DOTS? Yuri Danylyuk, Dmitri Romanov, and Gregory Auner, Wayne State University, Dept of Electrical and Computer Engineering, Detroit, MI.

We have investigated $In_xAl_{1-x}N$ layers on sapphire and silicon substrates with and without thin buffer layers of AlN. The value of x varied from 0 to 1. The AFM images of the structure demonstrate a large number of nanobumps. In a typical case of $x = 0.44$ the average size of a nanobump is 800 Åwhile the thickness of the underlying $In_xAl_{1-x}N$ layer is about 600 Å; the density of nanobumps is 5×10^8. The nanobumps are connected to one another through the underlying conducting layer and therefore seem unable to confine electrons. Besides, they are too large to provide effective electron quantization. However, our spectrophotometric measurements of the bumpy structures indicate additional peaks that can be only associated with additional energy levels, because high resolution X-ray diffraction scans (XRD) show no indication of face segregation. (The films exhibit only the (0002) and (0004) XRD peaks.) Our suggestion is that the built-in electric field from the strained layer (the strain was determined through Raman spectroscopy) pushes the charge carriers toward the tops of the nanobumps, causing effective isolation of the nanobump electrons and their quantization. Thus, the system of nanobumps emerges as a collective of quantum dots of a new kind. We present theoretical estimations of the electron confinement energy and density of states, which are in good agreement with the experimental data.

I6.30
PHASE SEPARATION IN InGaN EPITAXIAL LAYERS. A.N. Westmeyer and S. Mahajan, Department of Chemical and Materials Engineering and Center for Solid State Electronics Research, Arizona State University, Tempe, AZ.

Epitaxial layers of InGaN were deposited by metalorganic chemical vapor deposition on a GaN layer / sapphire substrate in order to investigate phase separation in the GaN-InN system. The In-contents varied from $x = 0.09$ to 0.31. Plan-view images obtained by transmission electron microscopy reveal a domain structure within which the composition is periodically modulated. Satellites appear around the fundamental reflections in the diffraction pattern. The spacing between the satellite and the reflection can be related to the wavelength of the modulations. Equations are derived for modulations in the $[10\bar{1}0]$ and $[11\bar{2}0]$ directions. Modulations were measured in the $[10\bar{1}0]$ direction and found to be about $\lambda = 3.2$ nm for all samples. Strain energy considerations explain the observation of modulations along different directions.

I6.31
OPTICAL AND CATHODOLUMINESCENCE STUDIES OF HIGH-INDIUM-CONTENT InGaN MULTIPLE QUANTUM WELLS. Yong-Hoon Cho, S.K. Lee, H.S. Kwak, S.K. Lim, K.H. Park, K.S. Lim, Chungbuk National University, Department of Physics, Cheongju, KOREA; S.N. Lee, O.H. Nam, M.S. Seon, Y.J. Park, Samsung Advanced Institute of Technology, MD Laboratory, Suwon, KOREA; H.M. Kim, T.W. Kang, Dongguk University, Quantum-Functional Semiconductor Research Center and Department of Physics, Seoul, KOREA.

We report on the optical emission and cathodoluminescence characteristics of InGaN multiple quantum wells with high In content grown by metal-organic chemical vapor deposition. The influence of In content in the InGaN active layer on various optical characteristics was investigated by photoluminescence (PL), cathodoluminescence (CL), optically pumped stimulated emission (SE), and time-resolved PL spectroscopy. PL spectra and integrated PL intensity of the InGaN quantum wells were measured as a function of temperature. The 300 K PL emission peak energy from the InGaN quantum well samples varied from ∼390 nm to ∼510 nm with increasing In content. Optically pumped SE experiments were performed to generate high-density carriers in the InGaN active region. We observed an increase in the InGaN emission peak energy with increasing excitation intensity, as well as a higher SE peak energy than the PL peak energy for all the samples. These features were enhanced as In content was increased, so that the difference between the SE and PL peak energy increased with increasing In content. Using the integrated PL intensity and the lifetimes measured by time-resolved PL, we extracted the radiative and nonradiative recombination lifetimes as a function of temperature. To investigate spatially resolved optical properties of the InGaN samples, we measured CL spectra and CL wavelength images. A phase separation and clustering were clearly observed for high-In-content InGaN quantum well samples. A relationship between spatially resolved CL images and other optical characteristics of the InGaN quantum wells with high In content will be given.

I6.32
OBSERVATION OF DEEP DEFECT IN PROTON IRRADIATED AlGaN THIN FILMS. Qiaoying Zhou, Jing Chen and M.O. Manasreh, Department of Electrical and Computer Engineering, University of New Mexico, Albuquerque, NM; M. Pophristic and Ian T. Ferguson, EMCORE Corporation, Somerset, NJ; Sergei Kucheyev and C. Jagadish, Department of Electronic Materials Engineering, Research School of Physical Sciences and Engineering, The Australian National University, Canberra, AUSTRALIA; B.D. Weaver, Naval Research Lab, Washington, DC.

Optical absorption measurements were used to investigate deep defects in proton (hydrogen) irradiated doped and undoped AlGaN thin films grown on sapphire substrates. Several samples were irradiated with proton with energies ranging between 10 keV and 1 MeV. In certain samples, multiple-energy ion implantation was found necessary to produce a defect, which is responsible for the absorption band observed at 4.61 eV with a shoulder at around 4.10 eV from the band edge. Furnace thermal annealing of the irradiated samples show that this absorption band start to anneal out at temperature as low as 200°C. Combined isochronal and isothermal annealing in the temperature range of 200- 500°C shows that the activation energy (enthalpy associated with the migration process) of this defect is a round 0.230eV. This leads us to conclude that this absorption band is due to a N-vacancy related defect. It is observed that the peak position energy of the absorption band due to this defect is shifted depending on the Al mole fraction in good agreement with the theoretical predictions. Results on whether or not this defect is following the conduction band minimum will be presented. It is also observed that the band edge absorption of the AlGaN is blue-shifted in the proton irradiated samples. The bowing factor was estimated as the Al mole fraction is increased from 0 to 60%.

I6.33
MICRO-RAMAN STUDY OF FRÖHLICH MODES AND CATHODOLUMINESCENCE MICROANALYSIS OF GaN COLUMNAR NANOSTRUCTURES. I.M. Tiginyanu, Laboratory of Low-Dimensional Semiconductor Structures, Technical Univ of Moldova, Chisinau, MOLDOVA; M.A. Stevens-Kalceff, Dept of Applied Physics, Univ of Technology, Sydney, AUSTRALIA; G. Irmer, J. Monecke and A. Sarua, Technical Univ, Freiberg, GERMANY; S.M. Hubbard, D. Pavlidis and V. Valiaev, Dept of Electrical Engineering and Computer Science, Univ of Michigan, Ann Arbor, MI.

GaN columnar nanostructures fabricated by electrochemical dissolution of MOCVD-grown layers have been studied by micro-Raman scattering (RS) and micro-cathodoluminescence (CL) techniques. Nanostructuring was found to lead to more than an order of magnitude increase in the RS intensity accompanied by a breakdown of the polarization selection rules. Apart from that, new modes at 640 and 716 cm^{-1} were observed in the frequency gap between transverse optical and longitudinal optical bulk phonons. We present a Raman line-shape theoretical analysis based on the effective dielectric function of a composite that brings to light the Fröhlich character of the new modes. CL microanalysis was carried out at accelerating voltages 5-15 keV in the temperature interval from 80 to 300 K. Both spectral and spatial distribution of CL was studied. The near-band-edge emission in nanostructured GaN showed a short-wavelength shift in comparison with that of bulk GaN. Monochromatic CL images taken from the same areas of samples exhibited an anti-correlation in the spatial distribution of near-band-edge and visible (2.2 eV) CL. During irradiation exposure, attenuation of near-band-edge and visible CL by the electron beam was evidenced, the effect being more pronounced for the UV emission. Taking into account the obtained results, new schemes for optical phonon engineering and controlling electron-phonon interaction in gallium nitride are proposed. The role of surface in defining emission characteristics of GaN nanostructures is discussed.

I6.34
MECHANISM OF THE INTERSUBBAND-SCATTERING IN MODULATION-DOPED AlGaN/GaN HETEROSTRUCTURES. Z.W. Zheng, B. Shen, Y.G. Zhou, R. Zhang, Y. Qian, J. Liu, H.M. Zhou, Y. Shi, Y.D. Zheng, National Laboratory of Solid State Microstructures and Department of Physics, Nanjing University, Nanjing, CHINA; J.P. Jiang, G.Z. Zheng, S.L. Guo, J.H. Chu, National Laboratory for Infrared Physics, Shanghai Institute of

Technical Physics, Chinese Academy of Sciences, Shanghai, CHINA; T. Someya, Y. Arakawa, Research Center for Advanced Science and Technology and Institute of Industrial Science, University of Tokyo, Tokyo, JAPAN.

Due to its excellent properties, AlGaN/GaN heterostructures have attracted great attentions in its application in high temperature, high frequency and high power electronic devices. Due to the large conduction band offset and the large piezoelectric field in AlGaN/GaN heterostructures, the electrons are confined to a very narrow stripe in the triangular potential well at the heterointerface. This leads to the quantized energy levels of the first two subbands separated as large as about 100 meV. It has been confirmed that the mobility of the two-dimensional electron gas (2DEG) in the triangular well at the heterointerface of AlGaN/GaN heterostructures is affected by the inter-subband scattering as that in AlGaAs/GaAs heterostructures. In this study the inter-subband scattering of the 2DEG in modulation-doped $Al_{0.22}Ga_{0.78}N$/GaN (AlGaN/GaN) heterostructures with various thickness of the AlGaN layer were studied by means of magnetotransport measurement at low temperatures and high magnetic fields. It is found that the inter-subband scattering of the 2DEG depends weakly on temperature when temperature is below 10 K. A sudden increase in the inter-subband scattering occurs when temperature is higher than 10 K. The relaxation degree of the AlGaN layer on GaN has the influence on the transfer temperature. It suggests that the inter-subband scattering is dominant by the alignment of staircases of the Landau levels corresponding to the different subbands when temperature is lower than 10 K, and changes to be dominant by the acoustic phonons via deformation potential and the piezoelectric potential at the heterointerface when temperature is higher than 10 K.

I6.35
INFLUENCE OF GROWTH TEMPERATURE ON INTENSITY OF BLUE EMISSION FROM ARSENIC DOPED GALLIUM NITRIDE FILMS GROWN BY MBE. A.J. Winser, S.V. Novikov, R.P. Campion, T. Li, C.T. Foxon, University of Nottingham, School of Physics and Astronomy, Nottingham, UNITED KINGDOM; I. Harrison, University of Nottingham, School of Electrical and Electronic Engineering, Nottingham, UNITED KINGDOM.

We have recently observed very strong blue emission at room temperature in As-doped GaN layers grown by Plasma-Assisted Molecular Beam Epitaxy (PA-MBE) on sapphire substrates using both arsenic dimers and tetramers. The photoluminescence from the As-doped GaN consists of three main bands, UV excitonic emission at 3.4eV, UV emission at 3.2eV and a rather strong blue band centred at 2.6eV. The intensity of the blue emission at room temperature of the As-doped samples is more than an order of magnitude stronger than the band edge emission in undoped GaN samples and can be seen at room temperature in normal lighting. We have studied the influence of the growth temperature on the intensity of optical emission from such films. As-doped GaN films were grown by PA-MBE in the temperature range 500-800°C. We observe a strong dependence of the intensity of the blue emission on the growth temperature. The intensity of this blue emission decreases with decreasing growth temperature from 800°C. At the same time the morphology of the films also changes with the formation of Ga droplets on the surface at low temperatures. A model to describe this observed behaviour is proposed.

I6.36
TEMPERATURE DEPENDENT STUDIES OF OPTICAL ABSORPTION EDGE IN $In_xAl_{1-x}N$ THIN FILMS. Y.V. Danylyuk, M.J. Lukitsch, G.W. Auner, Dept. of Electrical and Computer Engineering, Wayne State University, Detroit, MI; D. Haddad, R. Naik, Dept. of Physics, Wayne State University, Detroit, MI; V.M. Naik, Department of Natural Sciences, University of Michigan-Dearborn, Dearborn, MI.

The electronic structure and consequently the dielectric function of alloy semiconductors are influenced by several internal and external parameters, like composition, defects, strain, temperature etc. Here, we report the temperature (70-730 K) induced changes in the optical absorption edge of $In_xAl_{1-x}N$ epitaxial layers. This knowledge is important to distinguish, for example, between (quantum) size effects and strain. A series of $In_xAl_{1-x}N$ alloy films (thickness ~150 nm) with increasing In concentration (~15% increment) were grown by plasma source molecular beam epitaxy on sapphire (0001) substrates. X-ray diffraction measurements confirm a wurtzite crystal structure of alloy films with good crystallinity and lack of alloy segregation. The optical absorption edge shows a red shift with increasing temperature similar to other semiconductors with diamond or zincblende structure. For example, the $In_{0.32}Al_{0.68}N$ sample shows a linear temperature dependence of the absorption bandgap with a coefficient of -0.23 meV/K for T > 400 K. We also observe a reproducible shoulder in the absorption edge in the alloy samples for T < 200 K. The possible reasons for this observation will be discussed.

I6.37
ELECTRICALLY ACTIVE DEFECTS IN AlGaN ALLOYS GROWN BY MOCVD. Djelloul Seghier and Haflidi Petur Gislason, Science Institute, University of Iceland, Reykjavik, ICELAND.

Because of its large tunable direct band gap, ranging from 3.4 to 6.2 eV, and high saturation drift velocities for electrons, AlGaN is ideally suited for high power, high temperature and high frequency electronic devices. When undoped, AlGaN layers tend to be $n-$type, and for many years it was the high concentration of unintentional donors that prevented AlGaN from being utilised for practical devices. Recent advances in growth techniques allow a dramatic reduction of the donor concentration from 10^{19}-10^{20} cm^{-3} to concentrations below 10^{17} cm^{-3}. Yet residual donors remain very much an issue, especially in $Al_xGa_{1-x}N$ layers, and their origin is still unclear. They have often been attributed to defects related to nitrogen vacancies. So far the studies of localized centers have mostly focused on GaN, and few studies have been reported on electrically active defects in AlGaN layers in a wide range of compositions [1,2] In this work, we investigated two series of MOCVD-grown $Al_xGa_{1-x}N$ samples with the Al compositions $x = 0.1$ and $x = 0.3$ and different free electron concentrations. Shallow and deep centers were investigated using electrical characterization methods: capacitance versus temperature, photocapacitance and DLTS. The capacitance versus temperature measurements show the presence of a significant freeze-out of free electrons corresponding to a binding energy of about 90 meV in the sample with $x = 0.1$ and 118 eV in the sample with $x = 0.3$. Using DLTS and photocapacitance we observe other donor centers with various activation energies. The positions of these centers seem to depend on the alloy composition and are deeper in the sample with a higher Al content x. Moreover, we observe a hysteris in the $I - V$ and $C - V$ measurements from the sample with higher x. We correlate this long relaxation phenomenon with the presence of interface defects between Au and the AlGaN layer which become more significant with increasing x. The effect of annealing the materials is being studied and its effect on the activation energies of the observed donors will be reported. 1. H.G. Lee, M. Gershenzon, and B.L: Goldenberg, J. Electron. Mater. 20, 621 (1991). 2. E.J. Miller, X.Z. Dang, H.H. Wiwelder, P.M. Asbeck, and E.T. Yu, J. Appl. Phys. 87, 8070 (2000).

I6.38
ELECTRICAL AND OPTICAL STUDIES OF Si-IMPLANTED GaN. James A. Fellows, Yung Kee Yeo, Robert L. Hengehold, Air Force Institute of Technology, Wright-Patterson AFB, OH; Leonid Krasnobaev, Implant Sciences Corp, Wakefield, MA.

Silicon is widely used as a donor in group-III nitride device technology. However, the study of Si-ion implantation in GaN is still in its early stage. Therefore, the electrical and optical properties of Si-implanted GaN have been investigated as a function of ion dose, implantation temperature, and anneal temperature using Hall-effect measurements and photoluminescence. Implantation of Si was made into MBE-grown GaN capped with 500 Å AlN at 200 keV at room temperature and 800°C with six different doses ranging from 1x10^{13} to 5x10^{15} cm^{-2}. The samples were proximity cap annealed from 1050 to 1400°C for either 5 min or 15 s using conventional furnace or rapid thermal annealing. For any given dose, electrical activation efficiencies and mobilities increase as the anneal temperature increases from 1050 to 1250 or 1300°C. For a sample implanted with a dose of 5x10^{15} cm^{-2} and annealed at 1250°C for 18 s, an apparent electrical activation efficiency as high as 97% was obtained. Activation increased substantially with both implantation temperature and implantation dose. The results of temperature-dependent Hall measurements reveal the presence of a degenerate n-type interfacial layer. Therefore, more careful interpretation was used in estimating the electrical activation efficiency. Photoluminescence measurements were also performed in an effort to better understand the electrical activation behavior of the Si implants in GaN, and an attempt was made to correlate the Hall data with the luminescence spectra.

I6.39
OPTICAL AND STRUCTURAL PROPERTIES OF Mn-IMPLANTED GaN FILMS. R. Zhang, J. Xu, J. Li, X.Q. Xiu, S.L. Gu, B. Shen, Y. Shi and Y.D. Zheng, Department of Physics, Nanjing University, Nanjing, CHINA.

The role of Mn, a transition metal, in GaN is not well understood yet. Moreover, a high ferromagnetic Curie temperature is theoretically predicted to be realized in (Mn, Ga)N materials. In this work MnGaN films are prepared by the Mn-ion implantation and optical and structural properties of these films are investigated. The GaN films were grown by MOCVD with standard two-step growth procedure. High-dose Mn ions were implanted into the GaN films under 150kV. Three Mn atomic concentrations of 4.4_10^{20}, 1.1_10^{21}, 1.54_10^{21} cm^{-3} were designed to fabricate MNGaN films, respectively. Photoluminescence and photoluminescence excitation measurements

were carried out to study the optical properties of Mn-doped GaN. A new luminescence band around 2.82eV was observed in these Mn doped-GaN samples. The structure analysis reveals that the Mn doped samples have a good crystal quality as the pure GaN after annealed. That Mn atoms occupy substitutional position of Ga is experimentally proved. X-ray diffraction and Raman scattering measurements were employed to study the structural properties of MnGaN materials.

I6.40
INTERFACE ROUGHNESS, LOCALIZATION AND RADIATIVE EFFICIENCY IN InGaN/GaN LIGHT EMITTERS. Madhusudan Singh, Jasprit Singh, Univ of Michigan, Ann Arbor, MI.

Quantum wells based in InGaN and GaN have been actively studied over the past several years for light emission. It has been seen that in spite of substrate mismatch related dislocation densities of $\sim 10^7$ - 10^8 cm^{-2}, one can have reasonable quantum efficiencies in these quantum wells. In this paper, we will explore how carrier localization influences radiative efficiency in InGaN/GaN quantum wells. Due to very high interface polar charge at the InGaN / GaN interface, there is a large electric field that forces electrons and holes very close to the interface. As a result, interface disorder has a profound effect on carrier localization. We examine this effect using a self-consistent 3-dimensional solution of the Schrödinger equation with the Poisson equation. We find that as a result of disorder, low-lying electronic states are localized (i.e., are quasi 0-dimensional instead of quasi 2-dimensional) and are thus "protected" from dislocations. In the presence of dislocations, interface roughness therefore has a positive effect on radiative efficiency. Carrier densities for significant light emission are $\geq 10^{12}$ cm^{-2}, which implies that if localization is to play an important role in improving radiative efficiency, 10^{12} cm^{-2} or more of the electronic states should be localized. We find that this this occurs when interface roughness (or height of interface islands) is $\sim$3 monolayers. The localized states have wavefunctions that have lateral extent of $< 1000Å$. As a result, electrons and holes that occupy them don't sense dislocations which are spaced at $\sim 1\mu$ m. We find that if the interface quality is good (i.e., interface roughness is $\sim$1 monolayer) only $\sim 10^{11}$ cm^{-2} electrons are localized and radiative efficiency will suffer. The message of our study is : in presence of dislocations, a highly disordered InGaN/GaN structure will have better radiative efficiency. Detailed correlation between disorder, localization and radiative efficiency will be presented.

I6.41
ELECTRICAL AND OPTICAL PROPERTIES OF DEEP LEVELS RELATED TO POINT AND EXTENDED DEFECTS IN GaN EPILAYERS. A. Castaldini, A. Cavallini, L. Polenta, INFM and Dipartimento di Fisica, Universitá di Bologna, Bologna, ITALY; N. Armani and G. Salviati, MASPEC-CNR, Parma, ITALY.

The electrical and optical activity of defects in gallium nitride layers grown by hydride vapor phase epitaxy on a sapphire substrate was investigated. The epilayers were irradiated with 24 GeV protons at a fluence of 7.5 diamond 10^{13}cm-3 to investigate the origin of the defects. Electron beam induced current (EBIC) and low temperature cathodoluminescence (CL) analyses were performed before and after irradiation and their results compared to get information on the role that the deep levels associated to defects play in the radiative and non-radiative recombination mechanisms. Spectral photocurrent analyses were also carried out. They show four clearly separated carrier emissions underneath the broad yellow band typical of GaN. The wavelength emissions closely correspond to the photoluminescence transitions (blue, green, yellow and red) reported in the literature. It was found that irradiation dramatically decreases the photocurrent peaks corresponding to the yellow and, to a less extent, the blue emission, while enhances the green one. These findings were interpreted also on the basis of monochromatic CL results. DLTS analyses were carried out in planar as well as in cross-sectional geometry. They revealed that two traps at (Ec- 0. 21) eV and (Ec- 0.26) eV exist, both also in as-grown material, and that their concentration dramatically changes after irradiation. Their filling kinetics demonstrates that the trap at (Ec- 0. 21) eV is related to isolated point defects while the trap at (Ec- 0.26) eV is associated to dislocations.

I6.42
APPLICATION OF AMORPHOUS GaN FOR ELECTRO-LUMINESCENCE DEVICE. Tohru Honda, Hideo Kawanishi, Kohgakuin Univ, Dept of Electronic Engineering, Tokyo, JAPAN.

We report the vacuum evaporation of GaN thin films using a GaN powder (5N) for GaN-based Electroluminescence devices (ELDs). The crystal structures of evaporated GaN layers were amorphous, which was confirmed using RHEED patterns. Auger electron spectra revealed that the layers have exceeded Ga metal. Photoluminescence spectra of bluish-white color were observed at RT, whose starting energy located around the bandgap energy of the h-GaN crystal. ELDs were fabricated using evaporated GaN layers. The double SiO_2 dielectric layers were used as insulators in the ELDs. Cr metals were used as top and bottom electrodes. The thickness of deposited GaN layer was around 10 nm. The thickness of both insulators sandwiching the GaN layer was 200 nm. The bluish-white light emission was observed from the GaN-based ELD under the AC operation at RT. Although the emission intensity was weak, the electroluminescence spectra started from the bandedge of h-GaN.

I6.43
CONDUCTION BAND DENSITY OF STATES AND TRANSPORT PROPERTIES OF InGaAsN. Czeslaw Skierbiszewski, Piotr Perlin, Przemek Wisniewski, Tadeusz Suski, High Pressure Research Center, PAS, Unipress, Warszawa, POLAND; Wolfgang Jantsch, Institut fur Halbleiter- und Festkoerperphysik, Johannes-Kepler-Universitaet, Linz, AUSTRIA; John F. Geisz, National Renewable Energy Laboratory, Golden, CO.

In spite of the large interest in InGaAsN due to its potential application in infrared optoelectronics understanding of the transport properties of this material is still unsatisfactorily. The origin of the low electron mobility, doping limits, properties of the different dopants remain subject of intense studies. Also the effect of large potential fluctuations due to the presence of nitrogen (evidenced in photoluminescence experiments) on the transport properties has not been investigated. In the first part of this work we determine experimentally the strong nonparabolicity of the CB for $In_{0.03}Ga_{0.97}As_{0.99}N_{0.01}$. The CB dispersion was deduced from electron effective mass determined in far infrared reflectivity (plasma edge) and Hall effect measurements. In the second part we have studied the transport properties of the n-InGaAsN layers. The Hall effect and conductivity measurements for $In_{0.03}Ga_{0.97}As_{0.99}N_{0.01}$ with Se doping level from 1x10^{17} cm^{-3} to 3x10^{19} cm^{-3} under pressure up to 2 GPa in the temperature range 4K-300K were performed. Since Se donor properties in GaAs was not investigated we also study GaAs:Se layers. In InGaAsN we found that electron concentration decreases when temperature is lowering or hydrostatic pressure applied. We make use of the knowledge of CB structure to analyze the transport data in order to determine the microscopic nature of the Se related deep states in InGaAsN crystals. The results are analyzed within two competitive models: i) assuming that Se creates deep, localized state, ii) that electrons are localized on the potential fluctuations of CB due to the perturbation originated from N. It seems that contrary to Si dopant, Se does not create metatstable DX-like state in GaAs and InGaAsN.

I6.44
OPTICAL PROPERTIES OF CUBIC AlGaN. Stephane Fanget, Catherine Bru-Chevallier, Gerard Guillot, INSA-Lyon, LPM, Lyon, FRANCE; Esteban Martinez-Guerrero, Denis Jalabert, Bruno Daudin, Henry Mariette, DRFMC-SP2M-LPSC, CEA, Grenoble, FRANCE; Gabriel Ferro, Yves Monteil, LMI, Universite Claude Bernard, FRANCE.

Due to their large band gap, gallium nitride and its ternary alloys with AlN are mainly used for U.V optoelectronic devices. Actually most studies are based on the wurtzite (hexagonal) phase as the growth of pure zinc-blende (cubic) phase is more difficult due to its metastable nature. However optimisation of Molecular Beam Epitaxy (MBE) growth conditions has led to improve the quality of cubic materials grown on 3C-SiC pseudo-substrates. Moreover, in nitride cubic phase it is possible to get rid of piezoelectric and spontaneous polarisation electric fields, which are always present in the hexagonal phase. Such huge electric fields may be detrimental to performance of optolelectronic devices as they cause a reduction of oscillator strength and of carrier confinement in quantum structures. This is favorable for the developpement of optoelectonic devices based on the nitride cubic phase. To design such devices, optical constants need to be precisely known for both c-GaN and c-AlGaN. But the determination of such constants for c-AlGaN remains scarce up to now in the literature. In this work we report optical characterisation of several cubic AlGaN layers grown by MBE on 3C-SiC pseudo-substrates with different aluminum concentrations ranging from 0 to 62%. Composition and thickness of epitaxial layers are checked by Rutherford Back Scattering measurements. Photoluminescence studies versus temperature will be presented and the nature of the band gap of cubic AlGaN alloys will be discussed. We recorded reflectivity spectra for several aluminium concentrations in the wavelength range 1.5 eV - 4 eV. The refractive indexes are determined by an analysis of the envelope of reflectivity spectra. By fitting experimental results with theoretical calculations of multilayer structure we can get precise determination of refractive index for an Al content between 0% and 62%, we obtain also qualitative information about roughness at AlGaN/SiC and SiC/Si interfaces.

I6.45
ELECTRON TRANSPORT IN AlN UNDER A HIGH-FIELD

CONDITION. Ramon Collazo, Raoul Schlesser, Amy Roskowski, Robert F. Davis, Zlatko Sitar, Dept of Materials Science and Engineering, North Carolina State University, Raleigh, NC.

The energy distribution of electrons transported through an intrinsic AlN film was directly measured as a function of the applied field, and AlN film thickness. Following the transport, electrons were extracted into vacuum through a semitransparent Au electrode and their energy distribution was measured using an electron spectrometer. Transport through films thicker than 90 nm and applied field between 200 kV/cm - 350 kV/cm occurred as steady-state hot electron transport represented by a Maxwellian energy distribution, with a corresponding carrier temperature. At higher fields (470 kV/cm), intervalley scattering was evidenced by a multi-component energy distribution with a second peak at the energy position of the first satellite valley. Electron transport through films thinner than 90 nm demonstrated ballistic electron transport under fields greater than 550 kV/cm. This was evidenced by a symmetric energy distribution centered at an energy above the conduction band minimum. This indicated that the drift component of the electron velocity was on the order of the "thermal" component. The velocity-field characteristic along with relaxation times in the order of 10^{-14} s and transient lengths of less than 80 nm were deduced from these observations.

I6.46
GROWTH OF AlN-SiC SOLID SOLUTIONS FOR CONDUCTIVE CLADDING LAYERS IN ULTRAVIOLET LIGHT EMITTERS.
Adrian Avramescu, Hideki Hirayama, Yoshinobu Aoyagi, RIKEN, Semiconductors Lab, Wako-shi, JAPAN; Satoru Tanaka, Hokkaido University, RIES, Sapporo, JAPAN.

One of the major barriers in the fabrication of ultraviolet emitters based on nitrides compound semiconductors is the lack of conductive p- and n- material for the cladding layers. The AlN-SiC solid solution is proposed as a possible candidate material to achieve these properties. Besides the potential for p and n-type conductivity similar to SiC, one should also emphasize the convenient bandgap tuning in the range from 6.2 eV down to 3.3 eV and the close matching of the lattice constant to that of the SiC substrate. Since it was first reported that AlN and SiC could form continous solid solutions there were just a few reports on the growth of AlN-SiC epitaxial layers suitable for semiconductor applications. Up to date, most of the research on this alloy was performed by sublimation epitaxial techniques because of the high temperatures required. In this work, low-pressure metalorganic chemical vapor deposition (MOCVD) of the AlN-SiC alloy is achieved by a special technique called sequencial supply epitaxy (SSE). The growth of AlN-SiC by SSE consisted in the alternate supply of the trimethyl aluminium and tetraethyl silane during the first sequence followed by the supply of ammonia and ethylene as the second sequence of the cycle. The relatively low temperature for growth was in the range 1200 to 1300°C. The SSE gives an increased migration of the species on the surface and also reduces the gas phase reactions of the Al and Si precursors with ammonia that promotes 3-dimensional growth. The growth initiation was studied by exposing the SiC substrate to one or a cobination of two of the precursors employed. This initial exposure will enhance a specific bonding at the interface and/or will modify the surface energy prior to the SSE. It was found that ethylene exposure greatly improves the quality of the epilayers in terms of morphology and density of defects. The composition of the AlN-SiC was determined by X-ray diffraction and electron spectroscopy chemical analysis (ESCA). Alloys with a high content of AlN were mainly investigated. The surface morphlogy and crystalline properties as a function of composition were investigated. The incorporation of SiC tends to decrease the quality of the epilayers. Catholuminescence and Hall effect measurements were employed to characterize the epilayers. The close relation between the alloy stoichiometry and the conduction properties is demonstrated.

I6.47
CONTROL AND CHARACTERIZATION OF NUCLEATION AND INTERFACE STRUCTURE IN GaN GROWTH BY HALIDE VAPOR TRANSPORT (HVT).
V. Tassev, D. Bliss, Q.-S. Paduano, M. Suscavage Air Force Research Laboratory, Hanscom AFB, MA; P. Bhaskara, B. Kang, and C. Sung, Dept. of Chemical Engineering, Center for Advanced Materials, University of Massachusetts, Lowell, MA.

High quality GaN epitaxial films are grown on sapphire using the halide vapor transport (HVT) process. The ambient pressure, flow rate, and V-III ratio have been investigated to determine their effect on nucleation and interface structure. High purity iodine is sublimed and carried by hydrogen over gallium to produce gallium iodide. Ammonia, introduced as the source of nitrogen, reacts downstream with the gallium iodide to produce GaN on the substrate surface. C-plane sapphire wafers with pre-deposited 1μm MOCVD films were used as substrates. Crystal quality is determined from the FWHM of x-ray rocking curves and cross-sectional TEM to determine the defect structure. The dislocation density is a strong function of growth temperature and gas pressure. For example, under certain conditions, the growth of threading dislocations can be prohibited at a growth interruption. In other cases, the growth of threading dislocations is continued through the interface between two layers. A simple model of the interface structure and dislocation growth mechanism will be presented.

I6.48
THERMAL DESORPTION OF DEUTERIUM FROM GaN(0001).
Y. Yang, J. Lee, and B.D. Thoms, Georgia State University, Atlanta, GA; D.D.Koleske and R.L. Henry, Naval Research Laboratory, Washington, DC.

The desorption of hydrogen atoms from GaN surfaces is an important step in GaN growth (by MOCVD and HVPE), doping (particularly Mg) and etching (e.g. RIE) processes. Both clean and hydrogenated surfaces have been previously characterized by the authors who have reported that H_2 does not react with GaN(0001) but that exposure to H atoms produces surface Ga-H species and changes in surface electronic structure. Temperature programmed desorption (TPD) from deuterated GaN(0001) surfaces is reported in this paper. Deuterium atoms were produced by passing molecular deuterium over a heated tungsten filament. TPD performed with a heating rate of 1 K/s shows recombinative desorption of D_2 peaks at 690 K with a smaller peak near 600 K. The relative intensity of the lower temperature feature is about one fourth that of the main desorption peak for a well-ordered surface but this ratio depends on surface preparation and sample history. By performing TPD with heating rates from .05 K/s to 8.0 K/s, the variation of peak temperatures yields a pseudo-first-order desorption energy of 1.1 eV with preexponential factor of $2x10^6$ s^{-1}. Both the preexponential factor and activation energy for desorption are lower than expected and not consistent with the lack of reactivity of this surface to molecular hydrogen. These results are interpreted as being due to multiple surface sites and the data is reanalyzed assuming a preexponential factor of $1x10^{13}$ s^{-1}. This analysis yields a desorption energy of 2.0 eV and predicts an adsorption barrier $\sim$0.9 eV for molecular hydrogen on GaN(1000) surface.

I6.49
RAPID CHARACTERIZATION OF DISLOCATION DENSITY IN FREE-STANDING HVPE GaN OBTAINED BY EXCIMER LASER-LIFT-OFF USING PLAN-VIEW TRANSMISSION ELECTRON MICROSCOPY.
Patrick J. Taylor, R.J. Molnar, J.M. Caissie, A.H. Loomis, L.J. Mahoney, K.M. Molvar, D.B. Hoyt, G.W. Turner. Lincoln Laboratory, Massachusetts Institute of Technology, Lexington, MA.

A technique for the rapid determination of the dislocation density and the relative dislocation population of heteroepitaxial gallium nitride grown on sapphire is presented. GaN films grown by HVPE were separated from their sapphire substrate, dimpled, ion-milled to electron transparency, and characterized using bright-field and centered dark filed plan-view transmission electron microscopy. Using the null-contrast invisibility criterion for the relevant dislocations and diffraction vectors, the dislocation distribution was deduced. Because the lowest energy screw dislocations do not satisfy the null-contrast criterion, they appear with low contrast in the plan-view images. The dislocation density was measured and the relative population of screw, mixed and pure edge dislocations was determined to be one-third pure screw and two-thirds pure edge or mixed. This ratio is roughly consistent similar measurements from cross-section analysis.

I6.50
DIRECT BONDING OF n-TYPE GaN AND p-TYPE SiC FOR HETEROJUNTION FORMATION.
Jaeseob Lee, T.E. Cook, R.F. Davis, and R.J. Nemanich, Dept. of Mat. Sci. & Eng and Dept. of Physics, North Carolina State Univ, Raleigh, NC.

The poor wetting of GaN on 6H-SiC(0001) substrates impedes direct nucleation and frequently results in GaN films of poor crystallinity. During MBE and MOCVD growth dislocations form to relax the strain energy as the layer thickness exceeds a critical value, and the threading dislocations associated with the misfits can cause leakage current in device operation. Direct wafer bonding is an alternative method of forming a heterointerface or heterojunction. The method of direct bonding enables the formation of atomic bonds across atomically flat surfaces of different materials without introducing threading dislocations. Recently, we have proposed that the polarity of the surface is an important factor in direct bonding of GaN and SiC. That is, a bonded couple can be produced with Ga-face GaN and C-face SiC. In this report, we discuss the structural and electrical properties of the bonded interface between n-GaN/p-SiC. Bonded couples were produced using 2H Ga-face (0001) GaN prepared by MOCVD growth onto an (0001) SiC wafer with a (conducting) AlN buffer layer. A 6H (0001) Si-face p-type SiC wafer was used for the

bonding pair. Resistances were less than 0.1 ohm-cm for the GaN film and greater than 1.0 ohm-cm of p-SiC. The sequential bonding process consisted of ex situ wet cleaning, in situ dry cleaning, ex situ bonding and in situ annealing. Ex situ wet cleaning with a final HCl dip was employed for the GaN and a final HF dip was used for SiC (each 1min). In situ dry cleaning includes ~800C 10min UHV annealing of SiC and ~550C 10min UHV annealing of GaN. The in situ UHV bonding process was accomplished at 1000C for 4hr with 5C/min heating and cooling rates. Optical inspection of the interface displayed a uniformly bonded interface over most of the central region of the wafer sections.

I6.51
AlGaN/GaN-BASED MOSHFETs WITH DIFFERENT GATE DIELECTRICS AND TREATMENTS. D. Mistele, T. Rotter, K.S. Röver[a], S. Paprotta[a], Z. Bougrioua[b], F. Fedler, H. Klausing, O.K. Semchinova, J. Stemmer, J. Aderhold, and J. Graul, Laboratory for Information Technology, University of Hannover, GERMANY; [a]Institute for Semiconductor Devices and Materials, University of Hannover, GERMANY; [b]INTEC, Ghent University - IMEC, Ghent, BELGIUM.

We have fabricated AlGaN/GaN MOSHFETs on MOCVD grown templates by using photoelectrochemical (PEC) growth of $Al_xGa_{2-x}O_3$, thermal oxidation, and SiO_2 as gate dielectric. Photoelectrochemical processing is a useful tool for smooth etching, dislocation sensitive etching, or for oxide formation which has a small density of interface states [1]. In addition the $Al_xGa_{2-x}O_3$ oxide has a high dielectric constant of about 10 compared to 3.9 of SiO_2.
In these studies we compared the MOSHFET structures to conventionally processed HFETs with Schottky gate in terms of threshold voltage V_{th}, transconductance g_m, gate leakage current, and knee voltage. In addition we focus on the effects of the surface treatments with respect to the electrical behavior of the heterostructures.
First preliminary measurements of the wet chemical (PEC) processed transistors show the lowest V_{th} of about -2V, together with low drain currents I_D of only 10 mA/mm and transconductances of only 6 mS/mm for the transistor structures. HFETs with Ni/Au Schottky gate processed on the same AlGaN/GaN layer show higher V_{th} (-3V) and I_D of 160 mA/mm and g_m of 40 mS/mm. The tandem approach combining a thin PEC-oxide with a PECVD deposited SiO_2 layer of 16 nm show best results for I_D = 261 mA/mm. For this transistor enhancement mode is possible (positive gate bias) and the structures can be depleted in reverse mode resulting in I_D 9 orders of magnitude lower (range of pA/mm).
In addition we processed one sample of the heterostructure by oxidizing in O_2 at 900°C for 15 min before depositing 19 nm SiO_2. This transistor works in normally off/enhancement mode. At 0V gate bias I_D is about 10 nA/mm, in depletion mode about 10 pA/mm, and in enhancement mode 2 mA/mm.
[1] T. Rotter, D. Mistele et al., J. Cryst. Growth **230/3 – 4**, 606 (2001)

I6.52
CHEMICAL ORIGIN OF THE YELLOW LUMINESCENCE IN WURTZITE GaN. S.O. Kucheyev, The Australian National Univ., Dept of Electronic Materials Engineering, RSPhysSE, Canberra, ACT, AUSTRALIA; M. Toth, Univ. of Cambridge, Cavendish Laboratory, Cambridge, UNITED KINGDOM; M.R. Phillips, Univ. of Technology, Sydney, Microstructural Analysis Unit, Sydney, NSW, AUSTRALIA; J.S. Williams, C. Jagadish, The Australian National Univ., Dept of Electronic Materials Engineering, RSPhysSE, Canberra, ACT, AUSTRALIA; G. Li, Ledex Corporation, Kaohsiung County, TAIWAN.

The chemical origin of the yellow luminescence (YL) band in GaN is studied by ion implantation and cathodoluminescence (CL) spectroscopy. Results indicate that H, C, and O, presumably in combination with point defects, are involved in the formation of the YL in GaN, while lattice defects alone (as well as the other species implanted such as B, N, and Si) do not give rise to YL. In addition to giving rise to YL, C-related complexes appear to act as efficient nonradiative recombination centers. Our data strongly suggests that several (at least two: H- and C-related) radiative recombination channels contribute to the formation of the YL band. The H-related YL band is slightly blue-shifted relative to the C-related YL band in the case of relatively high excitation densities. This H-related peak exhibits a DAP-like behavior (i.e., a blue-shift with increasing excitation density), while the position of the C-related peak does not show any detectable shift for the range of excitation densities used in this study. Based on this experimental data and results reported previously, the chemical origin of the YL band is discussed.

I6.53
ELECTRICAL FIELD DEPENDENCE OF DEFECT STATES IN GALLIUMNITRIDE IMPLANTED WITH HYDROGEN IONS. A. Krtschil, A. Kielburg, H. Witte, A. Krost, J. Christen, Institute of Experimental Physics, Otto-von-Guericke-University Magdeburg, GERMANY; A. Wenzel, Institute of Physics, University of Augsburg, GERMANY; B. Rauschenbach, Institute of Surface Modification Leipzig and Institute of Experimental Physics II, University of Leipzig, GERMANY.

Ion implantation is one of the most convenient techniques to realize pattern doping and has been successfully applied to a lot of semiconductor materials. For the group III-nitrides, this method provides the additional advantage to reach very high doping levels with high reproducibility. However, the implantation success is still affected by some difficulties. The main problem addresses the generation of implantation induced defect states with compensating impact which commonly overrule the primary doping effect. One possible approach to reduce these defect states is a co-implantation with hydrogen ions in order to utilize the passivating properties of hydrogen already known from doping experiments with magnesium. In order to characterize the impact of hydrogen, GaN layers grown by metal organic vapor phase epitaxy on sapphire were implanted with 20 keV-hydrogen ions with ion doses ranging from $10^{14}/cm^2$ to $10^{15}/cm^2$. The corresponding deep level spectra were analyzed using thermal and optical deep level transient spectroscopy (DLTS, ODLTS) and admittance spectroscopy (TAS, OAS). As a result, we observed the generation of intrinsic electron traps with thermal activation energies between 140 meV and 1.1 eV as well as of additional optically induced defect-to-band transitions at photon energies ranging from 1.8 eV to 2.4 eV. Besides these common features of ion implantation experiments, the hydrogen introduces a group of defect states with a significant electrical field effect. The bias voltage applied during the measurement cycles strongly influences the structure of the deep level spectrum as well as the whole emission behaviour of the distinct trap contributions very similar to a defect exclusively found in samples grown by reactive molecular beam epitaxy and tentatively discussed as dislocation-related [1]. Our work evidences a correlation to hydrogen. The properties of this peculiar defect group will be discussed in detail. [1] Z-Q. Fang, D.C. Look, W. Kim, H. Morkoc: MRS Internet J. F99, W11.84 (1999)

I6.54
POINT DEFECTS, PHOTOLUMINESCENCE AND ELECTRICAL PROPERTIES OF GaN BULK CRYSTALS CODOPED WITH BERYLLIUM AND MAGNESIUM. V. Ranki, K. Saarinen, Laboratory of Physics, Helsinki University of Technology, FINLAND; T. Suski, E. Litwin-Staszewska, H. Teisseyre, M. Bockowski, I. Grzegory, UNIPRESS, High Pressure Research Center, Polish Academy of Sciences, Warsaw, POLAND.

The point defects formed in Be and Mg doping and codoping of high-pressure grown GaN bulk crystals have been studied by combining photoluminescence, electrical characterization and positron annihilation experiments. Nominally undoped GaN crystals are highly n-type due to oxygen impurities. Adding Mg and/or Be during growth makes the material highly resistive. The photoluminescence characteristics depend heavily on the doping: Be induces a strong yellow luminescence whereas Mg doping decreases the intensity of the yellow band and induces blue luminescence. In codoped samples both blue and yellow bands exist and their intensities vary with the ratio of Be and Mg concentrations. Positron experiments indicate high concentrations of Ga vacancies in Be doped GaN but no vacancies in Mg-doped samples. In codoped material the concentration of Ga vacancies decreases when the ratio of Mg and Be concentrations increases. The concentration of Ga vacancies correlates with the intensity of the yellow luminescence associated with Be doping, suggesting that Ga vacancies or related complexes participate in the optical transition leading to the yellow emission. Most interestingly, the formation of Ga vacancies is promoted by the presence of Be, although the acceptor defects are generally expected to form less abundantly in semi-insulating than n-type material. We discuss possible explanations for the observed phenomena, in particular the formation of defect complexes involving both Be and Ga vacancies.

I6.55
CHARACTERISTICS OF DEEP CENTERS IN FREE-STANDING GaN. Z-Q. Fang, D.C. Look, Semiconductor Research Center, Wright State University, Dayton, OH; P. Visconti, C-Z. Lu, D-F. Wang, H. Morkoç, Electrical Engineering and Physics Department, Virginia Commonwealth University, Richmond, VA; S.S. Park, K.Y. Lee, Samsung Advanced Institute of Technology, Suwon, KOREA.

Deep centers in a 300-μm-thick free-standing GaN sample were characterized by deep level transient spectroscopy (DLTS), using Schottky barrier diodes (SBDs) fabricated on the Ga surface. The sample was grown by hydride vapor phase epitaxy, removed from its sapphire substrate by a laser separation process, and then polished by mechanical and wet-chemical methods. The deep centers can be classified into three groups. 1) Common deep centers, which are

observed in all SBDs, if the reverse bias is set at a low enough value (say, -2 V). The common centers are A_1 (1.0 eV), A (0.67 eV), B (0.59 eV), C (0.35 eV), and D (0.25 eV), and they are also present in other GaN epilayers, grown by various techniques. However, in the present sample, A_1 and C are related to surface damage. 2) Unstable deep centers, A' ($\sim$0.77 eV) and B' ($\sim$0.46 eV), which are observed in some SBDs, but not all. These two centers become more prominent under conditions of high reverse bias and wide filling pulse, and they can be introduced, transformed, or destroyed by short-term heating. Interestingly, they are never observed together. 3) Bistable deep centers, which are observed only infrequently. These centers show a type of hysteresis with direction of thermal scan (warm-up vs. cool-down). Also, their intensities depend strongly on electric field strength, and thus they can be easily missed if the reverse bias is set low. The possible origins of all of the centers will be discussed in connection with material growth and processing.

SESSION I7: QUANTUM WELLS

Chair: Chris G. Van de Walle
Wednesday Morning, November 28, 2001
Room 302 (Hynes)

8:30 AM *I7.1
LIGHT EMISSION FROM QUANTUM-DOT-LIKE STRUCTURES IN CUBIC GaN/InGaN/GaN QUANTUM WELLS. Klaus Lischka, University of Paderborn, Dept of Physics, Paderborn, GERMANY.

Group III-nitrides (GaN, InN, AlN) that crystallize in the hexagonal (wurtzite) structure are the most important compound semiconductors for the mass production of blue and green light emitting diodes. Quantum wells (QWs) containing InGaN form the active zone of these devices. It is a well-established fact that the luminescence of these QWs is red shifted with respect to the band gap energy of the respective InGaN layers. This has been explained to be due to excitons localized in Indium-rich regions. A quite different approach proposed that the photoluminescence red shift in strained InGaN QWs originates from band tail states, which are induced by piezoelectric and spontaneous polarization fields. On substrates with cubic symmetry III-nitrides can also be grown in a metastable, cubic (zinkblende) configuration. In c-InGaN no piezoelectric and spontaneous polarization fields can exist. Therefore it has been suggested that the investigation of cubic GaN/InGaN/GaN QWs can help to understand the process of light generation. In this paper the results of extensive experimental investigations of such structures are reviewed. Micro-Raman effect, photoluminescence and photoluminescence excitation spectroscopy, cathodoluminescence as well as high-resolution x-ray diffraction measurements reveal clear evidence that the emission from the QWs is related to quantum dot (QD)-like structures which are formed within the InGaN layers. We find that the strain in the layers can significantly influence the process of QD formation. These results and those from annealing experiments corroborate the assumption that a phase seperation process forms the In-rich QDs.

9:00 AM I7.2
ELECTRON AND HOLE CONFINEMENT IN GaInN/GaN AND AlGaN/GaN QUANTUM WELLS. A. Hangleiter, S. Lahmann, U. Rossow, Institute of Technical Physics, Technical University of Braunschweig, GERMANY; P.R.C. Kent, A. Zunger, National Renewable Energy Laboratory, Golden, CO.

Carrier confinement in quantum well structures is a crucial issue for light emitting devices like LEDs and lasers. Nevertheless, the band offsets for GaInN/GaN heterostructures are still insufficiently understood. Commonly, it is assumed that the small valence band offset of InN with respect to GaN of only 0.3 eV scales linearly to GaInN with relatively low In mole fraction. Together with strong polarization fields present in nitride heterostructures any small band offset severely affects carrier confinement. We show, on the basis of empirical pseudopotential calculations, that the strong bowing of the bandgap of GaInN, which is primarily due to bowing of the valence band edge, translates into a strongly composition dependent ratio of the conduction band offset to the valence band offset with respect to GaN. For common In mole fractions of 0-20% this leads to a reversal of the band offset ratio and to very weak electron confinement. Moreover, due to the strong bowing, even a type-II situation is possible for GaInN/GaInN heterostructures. These theoretical considerations are well in line with our experimental results on carrier confinement in asymmetric AlGaN/GaInN/GaN and AlGaN/GaN/AlGaN quantum wells. While AlGaN/GaInN/GaN structures exhibit a drastic piezoelectric field-induced asymmetry of transition energies and oscillator strengths, there is only little such asymmetry in similar asymmetric AlGaN/GaN/AlGaN structures. This can be explained consistently only if there is weak electron confinement for GaInN/GaN but strong electron confinement for GaN/AlGaN. This finding has severe consequences for the analysis of quantum well transitions in general and for LED and laser design in particular.

9:15 AM I7.3
ENHANCED LIGHT EMISSION INTENSITY IN InGaN QWS THROUGH AlInGaN STRAIN ENGINEERING. S.F. LeBoeuf, M.E. Aumer, B.F. Moody, P. Barletta, S.M. Bedair, Dept of Electrical and Computer Engineering, North Carolina State University, Raleigh, NC.

We report on the effects of strain-induced piezoelectric fields on both the transition energy and intensity for InGaN quantum well (QW) structures having GaN or AlInGaN quaternary cladding. It is found that the emission energy of compressive-strained GaN/$In_{0.08}Ga_{0.92}N$ quantum wells exhibits a strong well width dependence that cannot be explained by quantum confinement alone. In contrast, for unstrained AlInGaN/$In_{0.08}Ga_{0.92}N$ quantum wells, no emission energy dependence on well width is observed due to the absence of strain-induced piezoelectric fields (measured to be at least 0.6 MV/cm within strained $In_{0.08}Ga_{0.92}N$ quantum wells). Capacitance-voltage carrier profiling shows that the two-dimensional electron gas (2DEG) density and peak height in strained InGaN QWs increases linearly with QW width, due to piezoelectric accumulation of carriers inside the well. In contrast, the 2DEG density and peak height vary only modestly with well width for unstrained QWs. Of further interest, unstrained quantum wells demonstrate markedly higher light emission intensity than their compressive-strained counterparts for all well widths investigated. This is explained by the higher oscillator strength made possible in unstrained QWs due to the absence of strain-induced carrier polarization. Self-consistent modeling of strained and unstrained InGaN QWs, accounting for the effects of strain-induced polarization, readily explain these observations. The acquired data provide a direct experimental comparison of strained and unstrained InGaN QWs needed for the development of optimized nitride-based optoelectronic devices.

9:30 AM I7.4
PIEZOELECTRIC FIELD AND LOCALIZATION EFFECTS ON RECOMBINATION IN AlInGaN/InGaN QUANTUM WELL STRUCTURES UNDER TENSILE, COMPRESSIVE, AND ZERO STRAIN. Michael E. Aumer, S.F. LeBoeuf, B.F. Moody, P.T. Barletta, J.C. Roberts, S.M. Bedair, North Carolina State University, Dept. of Electrical and Computer Engineering, Raleigh, NC; K. Nam, J.Y. Lin, H.X. Jiang, Dept. of Physics, Kansas State University, Manhattan, KS.

Optical transitions in InGaN based quantum well (QW) structures subjected to compressive stress have been explained based on composition modulation and the accompanying carrier localization. The present work will address the issue of the degree of carrier localization when the InGaN well is subjected to no strain and tensile strain. This can only be realized through the use of AlInGaN quaternary alloys used to form AlInGaN/InGaN QW structures. Time-resolved photoluminescence and temperature dependent photoluminescence (PL) from 10 K to 300 K were used to investigate recombination behavior in AlInGaN/InGaN QW structures grown with strain ranging from compressive to tensile, including unstrained QWs. It was found that the radiative recombination rate for unstrained wells is much higher than that of strained wells due to the effects of the piezoelectric field. The difference in recombination rate results in a higher emission intensity for unstrained 3 nm and 9 nm quantum wells than for their strained counterparts. Also, it was found that the activation energy for nonradiative recombination was a strong function of strain and well width, with the highest activation energy occurring within the most highly strained wells. Evidence that recombination is strongly influenced by transitions from localized states corresponding to compositional fluctuations is provided by the energy dependence of PL lifetime, the peak emission energy dependence on temperature, and temperature dependence of PL spectral shapes. Furthermore, the energetic depth of the localizing potential minima, and hence the nature of the compositional inhomogeneities, are a strong function of strain. All characterization approaches utilized consistently indicate that InGaN compositional fluctuations, and the resulting carrier localization, can be reduced when InGaN QWs are grown under strain free conditions

9:45 AM I7.5
SIMILARITIES IN THE OPTICAL PROPERTIES OF HEXAGONAL AND CUBIC InGaN QUANTUM WELLS.
S.F. Chichibu, M. Sugiyama, T. Onuma, Univ. of Tsukuba, Inst. of Applied Physics, Ibaraki JAPAN; T. Kuroda, A. Tackeuchi, T. Sota, Waseda Univ, Depts of Applied Physics and Electrical, Electronics, and Computer Engineering, Tokyo, JAPAN; T. Kitamura, H. Nakanishi, Sci. Univ. of Tokyo, Dept of Electrical Engineering, Chiba, JAPAN; Y. Ishida, H. Okumura, National Inst.of Adv. Industrial Sci. and Technology (AIST), Ibaraki, JAPAN; S. Keller, S.P. DenBaars, U.K. Mishra, S. Nakamura, Univ of California, Santa Barbara, CA.

High-power InGaN LDs exhibiting long lifetime have been realized. However, the threshold current density of the LDs is known to drastically increase for the lasing wavelengths shorter than 390 nm or longer than 420 nm. In usual, the former is thought to be limited by insufficient carrier/optical confinement and the latter is believed to be due to the presence of strong internal electric field F, which is dominated by the piezoelectric polarization. Since InGaN QWs exhibit high quantum efficiency in spite of the presence of F and large number of TDs, recombination mechanisms in InGaN has been attracted much attention; the mechanism should be understood to improve device performances. In the present study, structural and optical properties of both wurtzite and zincblende InGaN QWs are investigated to discuss the origin of carrier localization, since the comparison of optical properties between them will give us a clue to distinguish the effect of polarization field from that of exciton localization. Fully-strained InGaN QWs of both hexagonal (h-) and cubic (c-) materials exhibited certain Stokes-like shifts and wavelength-dependent decay time even at room temperature, regardless of TD density. The c-InGaN films and QWs show a bit shorter lifetime, but the decay curve can be approximated by a stretched exponential from low temperature to room temperature. Since c-InGaN film does not suffer from either the piezoelectric field or localization due to thickness fluctuation, exciton localization is considered to be an intrinsic property of InGaN. Results of temperature-dependent lifetime measurement imply that the localized states have quasi-zero dimensional confinement at low temperatures but finite dimension between 0D and 2D above 150 K.

10:30 AM *I7.6
PIEZOELECTRIC FIELD AND ITS INFLUENCE ON THE PRESSURE BEHAVIOR OF THE LIGHT EMISSION FROM InGaN/GaN AND GaN/AlGaN QUANTUM WELLS. Tadek Suski, Piotr Perlin, Slawek Lepkowski, Henryk Teisseyre, Pawel Prystawko, Mike Leszczynski, Nicolas Grandjean, Jean Massies.

We used high-pressure to investigate the nature of light emission from a number of InGaN/GaN and GaN /AlGaN structures. The purpose of using hydrostatic pressure measurements was to elucidate the role of the Quantum Confined Stark Effect (QCSE) in comparison with contribution to the light emission coming from cation-content segregation. The latter effect may appear as an important factor for InGaN/GaN structures for which light emission takes place in ternary InGaN quantum wells or quantum boxes. In case of AlGaN/GaN structures light emission is generated in binary GaN material. With applying hydrostatic pressure to GaN/AlGaN quantum wells the pressure coefficient of emission energy shows a strong reduction with increasing width of the GaN well. Thus, it is suggestive to associate it with increasing built in-electric field coming from piezoelectric and spontaneous polarization. In case of InGaN/GaN we used layers/structures grown on bulk GaN crystals which show high uniformity of In incorporation. We found very drastic reduction of the pressure induced blue shift of light emission from structures showing low emission energy. This result is similar to the findings of pressure studies on InGaN/GaN structures grown on sapphire. Calculations based on kp method and linear elasticity theory show that i) the built-in electric field increases with pressure in GaN/AlGaN system leading to a reduction of light emission pressure coefficient, ii) the opposite result for InGaN/GaN quantum wells. However, taking into account nonlinear terms of piezoelectric polarization we get an increase of the electric field also for InGaN/GaN quantum wells. Findings of this work strongly support the idea that the main contribution determining a magnitude of emission energy in InGaN/GaN and GaN /AlGaN systems is related to QCSE.

11:00 AM I7.7
NANOSTRUCTURE OF InGaN EPILAYERS, QUANTUM WELLS AND QUANTUM BOXES. K.P. O'Donnell, Dept of Physics, University of Strathclyde, Glasgow, SCOTLAND, UK; J.F.W. Mosselmans, Synchrotron Radiation Department, CLRC Daresbury Laboratories, Daresbury, ENGLAND, UK; N. Grandjean, CHEA-CNRS Valbonne, Sophia-Antipolis, FRANCE.

Extended X-ray absorption fine structure (EXAFS) above the In K-edge of luminescent InGaN heterostructures provides a unique probe of local structure on an atomic length scale. Through a process of fitting the experimental spectrum, we can refine a model of the probable configuration (the atom type, co-ordination number and radial separation) of the first few shells of neighbouring atoms in the vicinity of a selected probe atom. We present here, for the first time, the In-edge EXAFS spectrum of an ultrathin, uncapped 'quantum box' (QB) sample and compare it to results we have obtained previously on thick luminescent InGaN epilayers with a range of composition. While the epilayers resemble simple alloys, more or less, the QB sample reveals itself to consist of *a two-phase mixture of InN and dilute InGaN alloy*. The use of EXAFS to distinguish the local In environments of different InGaN-based heterostructures is likely to provide key information to unlock the puzzle of the origin of luminescence in these important commercial semiconductors.

11:15 AM I7.8
OPTICAL SPECTROSCOPY OF InGaN/GaN MULTIPLE QUANTUM WELLS WITHOUT In SEGREGATION. B. Monemar, P. Paskov, J.P. Bergman, G. Pozina, Department of Physics and Measurement Technology, Linköping University, SWEDEN; M. Iwaya, S. Nitta, H. Amano, I. Akasaki, Department of Electrical Engineering and Electronics and High-Tech Research Center, Meijo University, Tempaku-ku, Nagoya, JAPAN.

We have investigated photoluminescence (PL) and cathodo-luminescence (CL) spectra of InGaN/GaN multiple quantum wells (MQWs), to model the optical data and correlate them with the structural properties. The MQWs were grown with MOVPE at about 800 C, and the In content was about 11% in these samples. The GaN barriers had a small In content, 1-2%. Areas with mass transport lateral overgrowth in the GaN buffer allowed a comparison between regions with different dislocation density. Comparison was also made with optical data obtained in similar contacted structures, where PL under varying bias as well as electroluminescence (EL) spectra could be studied between 2 K and 300 K. The data typically show two near bandgap PL peaks with different properties. None of these peaks is related to In segregation, possible models to explain these data are discussed.

11:30 AM I7.9
EXACT DETERMINATION OF INDIUM COMPOSITION INVOLVED IN InGaN CRYSTALLINE LATTICE IN InGaN/GaN MULTIQUANTUM WELLS USING ANOMALOUS X-RAY SCATTERING. Hyun Hwi Lee, Hyeon Woo Jang, Yong-Tae Moon, Seong-Ju Park and Do Young Noh, Department of MS&E, Kwangju Institute of Science and Technology, Kwangju, KOREA; Keng S. Liang, Synchrotron Radiation Research Center, Hsinchu, TAIWAN ROC.

We have determined exact amount of In composition in InGaN films and InGaN/GaN multiquantum wells using anomalous x-ray scattering(AXS) at both In and Ga K-edges. AXS utilizes the fact that the scattering cross-section of a specific atom changes anomalously as the energy of the probing x-rays varies across its absorption edge. This method, although difficult to apply, provides exact composition of thin films independent of their strain status. In this experiment we determined the exact amount of In composition involved in InGaN crystalline lattice using AXS at the InGaN(0002) Bragg peak. The value was compared to the one obtained from regular x-ray diffraction analysis which can be misleading due to the uncertainties of relaxed lattice parameters and elastic constants. In addition, the depth profile of In concentration was obtained from the angle-resolved x-ray fluorescence at grazing angles. The AXS and the angle-resolved x-ray fluorescence signals obtained near the In K-edge(27.94keV) are more sensitive to the In composition than those obtained near the Ga K-edge(10.367keV).

11:45 AM I7.10
EFFECT OF INDIUM CONTENT ON THE OPTICAL PROPERTIES OF THICK InGaN-EPILAYERS. F. Bertram, S. Srinivasan, L. Geng, F.A. Ponce, Department of Physics, Arizona State University, Tempe, AZ; T. Riemann, J. Christen, Institute of Experimental Physics, Otto-von-Guericke-University, Magdeburg, GERMANY; S. Tanaka, H. Omiya, and Y. Nakagawa, Nichia Corporation, Tokushima-ken, JAPAN.

Cathodoluminescence (CL) measurements were performed on a set of thick, state of the art, InGaN layers covering systematic a wide range of indium concentrations (x=0.03-0.20). The nominally 80nm thick layers were grown by MOVPE on 4μm thick GaN using a c-plane sapphire substrate. A comprehensively study of the evaluation of optical parameter with Indium content will be reported. A direct correlation between the structural and the luminescence properties on a microscopic scale is achieved by highly spatially resolved CL measurements. While in CL mappings the size of the areas with constant emission wavelength decreases with indium content, a similar change of the domain size is observed by AFM. At low indium concentrations, statistical fluctuations of the local indium content lead to Gaussian broadening of a single emission line. At $x>0.1$, phase separation is observed to result in a multimodal distribution of the peak wavelength, leading to additional low-energy peaks in CL overview spectra. Monochromatic CL images show a complementary behavior of the low-energy emission with respect to the main InGaN peak. The low-energy peaks are caused by single lines appearing at specific energies in the local spectra (at preferential indium concentrations). Using highly spatially resolved CL measurements we directly correlate these low-energy emissions to two characteristic structural defects seen at high indium concentrations: craters and needles. Two behaviors of the luminescence shifts were found when

going from the outside towards the center of a crater. In both cases the InGaN peaks shift to longer wavelengths. In one case a continuous red shift of the peak is observe, while in other cases abrupt changes of the peak wavelength between fixed wavelength positions are often observed. These features are closely correlated to the dislocations present in these materials.

SESSION I8: TRANSPORT AND OPTICAL PROPERTIES

Chair: Bo Monemar
Wednesday Afternoon, November 28, 2001
Room 302 (Hynes)

1:30 PM I8.1
ELECTRON TRANSPORT AND MAGNETOTRANSPORT IN AlGaN/GaN HETEROSTRUCTURES. Remis Gaska, Department of ECSE and CIEEM, Rensselaer Polytechnic Institute, Troy, NY and Sensor Electronic Technology, Inc., Latham, NY; W. Knap, M.S. Shur, Department of ECSE and CIEEM, Rensselaer Polytechnic Institute, Troy, NY; Asif Khan, J. Yang, G. Simin, Department of ECE, University of South Carolina, Columbia, SC; G. Kraczewski, HMFL, Tallahasee, FL.

We report on magnetotransport measurements in AlGaN/GaN heterostructures grown on sapphire, SiC, and bulk GaN substrates. The measurements were performed in the temperature range from 30 mK to 100 K in the magnetic fields up to 30 T. Both regular samples and samples with gated Hall bars were used. In the samples with the gated bar, the Schottky gate was deposited over the whole bar and allowed us to modulate the electron sheet density in the channel by applying bias to the gate. We investigated the temperature and carrier concentration dependences of the magnetoresistance and demonstrated that the magnetoresistance was negative in the magnetic fields up to 10 T in the temperature range from 30 mK up to 300 K. For example, at T= 4.2 K, in the sample on SiC, the electron Hall mobility was close to 11,000 cm^2/Vs in the magnetic field H = 1 T, and monotonously increased by more than 15% to μ = 13,000 cm^2/Vs at H = 8 T. These results are consistent with the new mechanism of the negative magnetoresistance recently proposed by Dyakonov and Dmitriev.[1]
References [1] M. Dyakonov and A. Dmitriev, PRB 2001, to be published.

1:45 PM I8.2
SINGLE ELECTRON TRANSPORT IN GaN COUPLED QUANTUM DOTS FORMED BY MOLECULAR BEAM EPITAXY. Koji Kawasaki[a,b,c], Kazuo Tsutsui[a,b] and Yoshinobu Aoyagi[a,b,c]; [a]Tokyo Inst Tech, Yokohama, JAPAN; [b]RIKEN, Wako, JAPAN; [c]CREST, JST, Kawaguchi, JAPAN.

Formation of coupled quantum dots (QDs) is important because quantum coherent states produced by the coupled QDs will produce new solid-state devices such as quantum logic gates. However, no one knows which material is suitable for realization of the devices. Material research is required from the viewpoints of dephasing time of the coherent state, device operation temperature, industrial easiness and so on. Quantum dot structure of wide band gap GaN and related nitride materials are of great interest since large conduction band offset of 2.3 eV at GaN/AlN interface provides strong electron confinement in their quantized levels and small dimension QD creates a large energy scale system. The dephasing time of an electron in the GaN quantum dots is also expected to be long because strong electric field due to spontaneous polarization confines the electron to surface regions away from the substrate. In this study GaN coupled QDs were fabricated using self-assembling technique by MBE and single electron transport in the coupled QDs were investigated by making single electron transistors (SET) for future device applications. After Ga nano-droplets formation on SiO_2/Si substrates, the droplets were annealed with an ammonia gas supply for crystallization. Then the GaN QDs were enlarged to form the coupled QDs by MBE technique and the surface was covered with a thin AlN layer as a tunneling barrier. SET using the coupled QDs was fabricated by a Au/Al metals lift-off process after electron beam exposure and development of a resist layer. The SET exhibited Coulomb blockade (CB) phenomena with large CB regions between 0.5 V to 0.8 V at 6K. Charge stability diagram of the device exhibited stochastic CB transport property and negative differential conductance. This origin of the phenomenon is considered to be resonant tunneling between zero dimensional states in coupled QDs.

2:00 PM I8.3
DETERMINATION AND CRITICAL ASSESSMENT OF THE OPTICAL PROPERTIES OF III-V NITRIDE HETERO-STRUCTURE MATERIALS WITH VACUUM ULTRAVIOLET SPECTROSCOPIC ELLIPSOMETRY IN THE 0.7 TO 9.0 SPECTRAL RANGE. N.V. Edwards, S. Zollner, A. Konkar, Motorola Materials and Structures Laboratories, Mesa, AZ; L.D. Madsen, Carnegie-Mellon University, Dept of Materials Science and Engineering, Pittsburgh, PA; O.P.A. Lindquist, K. Jarrendahl, Linkoping University, Department of Physics and Measurement Technology, Linkoping, SWEDEN; C. Cobet, N. Esser, Technical University Berlin, Institut fur Festkoeperphysik, Berlin, GERMANY; S. Peters, SENTECH Instruments GmbH, Berlin, GERMANY; D.E. Aspnes, NC State University, Department of Physics, Raleigh, NC.

Obtaining reliable values of optical constants and the ability to characterize band-to-band optical transitions over a relatively wide spectral range are the first steps toward enabling the eventual in-line optical metrology of any process. For the wide bandgap III-V Nitrides, this capability has historically been frustrated by the limited spectral range of conventional ellipsometers, difficulty in preparing surfaces, and a lack of high quality material. Progress has recently been made toward producing substrate material for nitride homoepitaxy, but until nitride substrates are routinely employed in optoelectronic manufacturing environments, thorough optical characterization of current substrate materials (α-Al_2O_3 and 6H-SiC) will also be crucial for properly modeling nitride optical dispersion. However, the characterization of these materials has itself been limited by many of the same problems. Towards a solution, we present a VUV SE data for both materials, obtained on SENTECH and Woollam commercial systems. The results are discussed in the context of bandstructure, optical transitions, and preparation/ characterization of abrupt surfaces. This is crucial for data interpretation: e.g., (1) though the VUV range allows for the identification of SiC higher-lying optical transitions, challenges associated with surface preparation meant that the main uncertainty in the data arose from the mathematical oxide overlayer correction. To investigate, qualifying SE measurements were performed to assess, in real-time, the efficacy of common surface preparation regimens to remove overlayers from SiC surfaces. (2) Though the stable surface of Al_2O_3 eliminates such problems, here an excitonic contribution to the spectra complicates the determination of optical constants and bandedge critical point energies, a factor not included in theoretical calculations of Al_2O_3 optical constants and heretofore unobserved in SE data. Finally, these results will be evaluated in the context of VUV SE optical models for data recently obtained on III-V nitride heterostructures grown, where possible, on both substrate choices.

2:15 PM I8.4
ANISOTROPY OF UV OPTICAL RESPONSE IN WURTZITE GaN COMPARED TO CdSe. Walter R.L. Lambrecht and Margarita Prikhodko, Department of Physics, Case Western Reserve University, Cleveland, OH.

Similarities and dissimilarities in the anisotropy of the UV optical response in wurtzite GaN with other wurtzite materials like CdSe were recently pointed out by Benedict et al.[1]. In CdSe, Cardona[2] identified two prominent features with the spin-orbit split $\Gamma_{5v} - \Gamma_{3c}$ transitions which are allowed only for $\mathbf{E} \perp \mathbf{c}$, whereas a third peak, present in both polarizations was tentatively associated with transitions at the edge of the Brillouin zone. Similarly, in GaN, Benedict et al. predict three prominent peaks between 4 and 10 eV of which one appears strong in both polarizations and the other two only in $\mathbf{E} \perp \mathbf{c}$ but the energy ordering of these features is different from CdSe. The optical response function for GaN in the UV region has so far only been measured in the $\mathbf{E} \perp \mathbf{c}$ polarization. Here, we analyze the origin of these optical transitions using the linear muffin-tin orbital band structure method and optical response calculations in both CdSe and GaN, including spin-orbit splitting effects. The imaginary part of the dielectric function $\varepsilon_2(\omega)$ is decomposed in individual band-to-band transitions and the prominent features are related to specific locations in the Brillouin zone by examining band differences plotted as function of wavevector. We find that the above mentioned similarity is coincidental, the peaks at higher energy that are suppressed in GaN in $\mathbf{E} \parallel \mathbf{c}$ originate from transitions along the $M - L$ line, not from the $\Gamma_{5v} - \Gamma_{3c}$ transition. The $\Gamma_{5v} - \Gamma_{3c}$ transition in GaN is a relatively weak feature, appearing on the low energy side of the first main peak, which so far has not been clearly identified experimentally. In CdSe, on the other hand, Cardona's explanation for the polarization effects is essentially confirmed by our calculations.
1. L.X. Benedict et al., Solid State Commun. **112**, 129 (1999)
2. M. Cardona, Solid State Commun. **1**, 109 (1963).

3:00 PM *I8.5
THE MICROSCOPIC MECHANISMS THAT RULE TIME RESOLVED SPECTROSCOPY AND ELECTRON-PHONON INTERACTION IN LOW-DIMENSIONAL NITRIDES. Bernard Gil, Centre National de la Recherche Scientifique, Université de Montpellier 2, Groupe d'Etude des Semiconducteurs, Montpellier, FRANCE.

The presentation begins by a presentation of a method based on the

Fourier transform of the reflectance spectrum of GaN-AlGan quantum wells that permits to obtain both oscillator strength (a probe of the efficiency of the coupling with the electromagnetic field) and radiative broadening parameters (a probe of the topological disorder). In the second part of the presentation, the recombination dynamics of excitons is compared for GaN-AlGaN and InGaN-GaN quantum wells and quantum dots. In the third part we examine the exciton-LO phonon interaction and show that it behave similarly for both GaInn-GaN quantum wells and quantum dots while such a similarity is not found for GaN-AlGaN low-dimensional systems. These findings are finally discussed in the context of simple modellings that include both the Quantum Confined Stark Effect and the localization phenomena.

3:30 PM I8.6
EXCITON SPECTRA OF AlN EPITAXIAL FILMS. T. Onuma[a], S.F. Chichibu[a], T. Sota[b], K. Asai[c], S. Sumiya[c], T. Shibata[c], and M. Tanaka[c], Univ. of Tsukuba[a], Waseda Univ.[b], NGK Insulators, Ltd.[c], Tsukuba, JAPAN.

Aluminum nitride (AlN) has a wide bandgap of 6.2 eV and can be applied for optical devices such as ultraviolet light source and detector as well as the substrate for the surface acoustic wave (SAW) devices. AlN, which crystallizes in a wurtzite structure, has three separate valence bands at Gamma point due to the crystal field splitting and spin-orbit splitting. There is an optical polarization selection rule for each band. Few studies have been carried out for this band structure, since the threading dislocation (TD) density has been too high to observe them. In the present study, two improved AlN thin films grown by metalorganic chemical vapor deposition (MOCVD) were investigated by optical reflectance (OR) and cathodoluminescence (CL) measurements. One is a C-plane AlN grown on C-plane sapphire substrate (sample 1) with low TD density (smaller than 10^{10} cm^{-2}) and the other is an A-plane AlN grown on R-plane sapphire substrate (sample 2). They showed different spectrum features due to the different optical polarized selection rules. Excitonic transition structures around 6.20 eV and 6.26 eV were first experimentally observed in the OR spectrum for the sample 1 at 8 K. The Kramers-Kronig analysis was performed for these structures. They are assigned to the ground state A- and B-,C- exciton resonances, respectively. The redshift of the energies with increasing temperature from 8 K to 300 K and comparison with the spectral feature of sample 2 support the above assignment. The crystal field splitting was first experimentally estimated to be 60 meV. The A-exciton emission was observed by CL measurement for the sample 1 at 77 K.

3:45 PM I8.7
INTERSUBBAND OPTICAL ABSORPTION AND ELECTRON RELAXATION RATES IN GaN/AlGaN COUPLED DOUBLE QUANTUM WELLS. J.D. Heber, C. Gmachl, H.M. Ng, S.V. Frolov, A.Y. Cho, Bell Laboratories, Lucent Technologies, Murray Hill, NJ; S.N.G. Chu, Agere Systems, Murray Hill, NJ.

Recent interest in intersubband (IS) transitions in semiconductor heterostructures with large band offset has been fueled by attempts to extend the wavelength range of IS-based optical devices to the fiber-optics wavelength range around ~1.55 μm. GaN/AlGaN-based heterostructures are of particular interest due to their large effective electron mass and large longitudinal optical phonon energy. Both are essential to achieve ultrafast electron relaxation at large transition energies. IS absorption in coupled GaN/AlGaN double quantum wells (DQWs) has been measured. The samples were grown by molecular beam epitaxy on sapphire substrate and with a large (0.65 or 0.9) AlN-mole fraction in the barriers. Peak absorption wavelengths as short as 1.35 μm and 1.52 μm were measured for a symmetric DQW of 12 Å wide wells coupled by a 10 Å wide barrier, which also showed evidence of excited-state anti-crossing. As expected, asymmetric DQWs displayed no such anti-crossing, and the ground-state anti-crossing energies were found to be much smaller - as a result of the comparatively large effective electron mass - than the energy broadening of individual transitions. The asymmetric DQWs displayed peak absorption wavelengths between 1.5 and 2.9 μm. The electron relaxation time, attributed to longitudinal optical phonon scattering, in isolated quantum wells has recently been measured to be ~370 fs at 1.55 μm. Excited state electron lifetimes of coupled DQWs are expected to be even shorter.

4:00 PM I8.8
POLARIZATION EFFECTS IN THE PHOTOLUMINESCENCE OF AlGaN AND AlInGaN BASED QUANTUM WELL STRUCTURES. Mee-Yi Ryu, E. Kuokstis, C.Q. Chen, J.P. Zhang, J.W. Yang, G. Simin, M. Asif Khan, Univ of South Carolina, Dept of Electrical Engineering, Columbia, SC; R. Gaska, M.S. Shur, Sensor Electronic Technology Inc., Latham, NY.

Nitride based quantum well structures with emission wavelength in the range of 330 - 350 nm are the key elements for solid-state white light sources. In these materials the spontaneous and piezoelectric polarization fields have a strong influence on the optical properties of the MQWs. Quaternary-based materials exhibit superior quality, better morphology and stronger emission. We have studied the internal electric field effects of (Al)GaN/AlGaN and AlInGaN/AlInGaN multiple quantum well (MQW) structures grown by metalorganic chemical vapor deposition and novel pulsed atomic layer epitaxy, respectively. The position of the emission peak and the nature of emission spectra depend on the excitation-power density (I_{exc}). This dependence can be attributed to localized states, polarization fields, quantum-confined Stark effect or band gap renormalization. In order to clarify the field effects in these material systems, the excitation-power dependent photoluminescence (PL) spectra were obtained using a pulsed excimer laser (193 nm) as an excitation source. We have measured the PL spectra of (Al)GaN/AlGaN and AlInGaN/AlInGaN MQWs with different well and barrier compositions. In both (Al)GaN/AlGaN and AlInGaN/AlInGaN MQWs a blueshift followed by a redshift of the PL peak position were observed with increasing I_{exc}, which we attribute to the screening of fields and band gap renormalization, respectively. In bulk AlInGaN material or in MQWs with thin well widths the blueshift was not observed, which means that unlike typical GaN/InGaN MQWs In incorporation in AlInGaN material in the amount required to fabricate smooth layers with strong emission at 330-350 nm does not create significant concentration of localized states. We have evaluated the internal field in MQW structures by comparing the experimental data to the simulations based on triangular quantum well model resulting from the polarization fields.

4:15 PM I8.9
TIME RESOLVED RESONANT RAMAN SCATTERING IN GaN. Axel Hoffmann, Axel Kaschner, Christian Thomsen,Technical University Berlin, Institute of Solid State Physics, Berlin, GERMANY.

Resonant Raman scattering on free and bound excitons in GaN at low temperatures is comprehensively investigated. The E2, A1(LO) and 2A1(LO) Raman modes are resonantly enhanced when the energy of the incoming photon matches the bound exciton energy or is slightly below. Whereas the polar LO modes are also subject to the Fröhlich interaction, the nonpolar E2 mode interacts only via deformation-potential interaction. This is reflected in the LO/E2 ratio which increases towards the excitonic resonances. Furthermore, we investigated the change in the decay behavior during the transition from phonon replica to resonantly enhanced phonon modes. As expected, the phonon replica exhibit the same decay constant as the bound exciton, whereas the decay of the phonons is dominated by a coherent fast component, which is only a few ps. However, we found a larger decay constant with a lower amplitude in the decay characteristic for all phonons. For excitation conditions below the bound excitons this second decay time is close to the measured free exciton decay constant. We suggest that the free exciton is the intermediate state for the resonance process in this region. Furthermore, the temporal behavior of the phonons near the resonance was studied using time-resolved spectroscopy. We found that the resonance process below the bound excitons is likely to proceed via the free exciton as intermediate state.

4:30 PM I8.10
MAGNETO-SPECTROSCOPY OF TWO-ELECTRON TRANSITION IN HOMOEPITAXIAL GaN. M. Wojdak[a], J.M. Baranowski[a], A. Wysmolek[a,c], K. Pakula[a], R. Stepniewski[a], M. Potemski[c], I. Grzegory[b] and S. Porowski[b]; [a]Insitute of Experimental Physics, Warsaw University, Warsaw, POLAND; [b]High Pressure Research Center Polish Academy of Sciences, Warsaw, POLAND; [c]Grenoble High Magnetic Field Laboratory, Grenoble, FRANCE.

Two-electron transition occurs when the exciton bound to a neutral donor (DBE) recombine and leaves the donor in an excited state. The two-electron transition energy is therefore lower than that of the principal DBE peak, by the difference in ground and excited state of the neutral donor. Without magnetic field the two-electron satellite is rather broad. In a magnetic field the two-electron satellite splits into several components. These two-electron satellite excitations have been studied in homoepitaxial GaN in magnetic fields up to 23T. For Faraday (B⊥c) and Voigt configuration (B⊥c) the two electron satellite clearly splits into 2s, 2p0, 2p and 2p- components. The total splitting between 2p and 2p- has been found equal to Landau energy. From these measurements a small anisotropy of electron effective mass has been for the first time for GaN detected, giving perpendicular 0.217 m_0 and parallel mass 0.213 m_0. It has been found that the experimental energies are well described by hydrogenic-like model in the whole range of magnetic fields with clear positive chemical shifts taking place for 1s and 2s states. It is argued that the donor responsible for the two electron transitions is connected with nitrogen vacancy. In addition to 2s, 2p0, 2p and 2p- excitation several spin flip transitions have been observed for B⊥c configuration. The energy of

spin flip observed in two electron transition agrees with the spin splitting found on the principal DBE line for B⊥c configuration.

SESSION I9: VAPOR PHASE EPITAXY
Chair: Randall M. Feenstra
Thursday Morning, November 29, 2001
Room 302 (Hynes)

8:30 AM *I9.1
HYDRIDE VAPOR PHASE EPITAXY OF GaN AND ITS PROPERTIES. Sungsoo Park, Seongkuk Lee, Kyoyeol Lee, Injae Song, Jaiyong Han, Samsung Advanced Institute of Technology, Suwon, KOREA; Sungho Choh, Seoul Branch, KBSI, Korea University Campus, Seoul, KOREA.

High quality GaN crystals with thickness varying 300 ~800 μm have been grown on sapphire substrates using the hydride vapor phase epitaxy(HVPE) technique. The surface of the sapphire substrate was treated with NH_3 gas at the initial stage of GaN crystal growth, and its effect on the quality of grown crystal has been investigated. The crystalline quality of GaN is found to be improved as the thickness increases. The density of the uniformly distributed dark spots observed in the micro PL map with ~300 μm thick GaN crystal is high 10^6 /cm^2, meaning that the HVPE grown thick GaN crystal is of superior uniformity. The shape of as grown and freestanding GaN films, respectively, is convex and concave viewed from the Ga surface. The origin of the convex shape of GaN films with the sapphire substrate is the difference of the thermal expansion coefficient between GaN and sapphire. The radius of curvature for the freestanding GaN crystal removed from the sapphire substrate was found to be approximately 1 m. It is observed that the Ga surface is better quality than the N surface from the etching, X-ray, and TEM analyses. It is also confirmed that the freestanding GaN wafer meets the quality that can be used for device fabrication.

9:00 AM I9.2
ELECTRICAL, THERMAL, AND STRUCTURAL PROPERTIES OF FREESTANDING GALLIUM NITRIDE. Robert P. Vaudo, Xueping Xu, Edward L. Hutchins, Jillian S. Testa, Joseph A. Malcarne, Allan D. Salant, and George R. Brandes, ATMI, Inc., Danbury, CT; Doru. I. Florescu and Fred H. Pollak, Physics Department, Brooklyn College of CUNY, Brooklyn, NY.

Freestanding GaN samples were produced by HVPE with thicknesses ranging from 100 to 400 μm and with a range of dislocation densities and background impurity concentrations. In this study, the electrical, thermal and structural characteristics were evaluated, as were their interdependent relationships. A predominance of mixed threading dislocations accounts for a dislocation density as low as 4×10^6 cm^{-2} for the thickest GaN material, as observed by plan view and cross section transmission electron microscopy. Defect decoration etching in hot phosphoric acid was also utilized to measure dislocation density. Dislocation density generally decreased with GaN thickness. The background impurity concentration also decreased from 5×10^{16} cm^{-3} to 5×10^{15} cm^{-3} over the thickness range examined. Thermal conductivity measurements were performed by both laser flash and scanning thermal microscopy methods; a brief comparison of these methods will be presented. For material with dislocation density less than 10^7 cm^{-2}, we measured thermal conductivity values as high as 2.2±0.2 W-cm^{-1}K^{-1} at room temperature. Based upon a fit to elevated temperature data, the thermal conductivity changes as 5.6exp(-3.5 × 10^{-3}T(K)). The thermal conductivity values for the HVPE GaN reported here are larger than values reported for GaN material grown by lateral epitaxial overgrowth. The lower background carrier concentration observed in HVPE GaN could be playing a significant role in achieving the higher thermal conductivity, offsetting the effect of a somewhat higher dislocation density compared to the LEO material tested. Still further improvements in thermal conductivity may be obtained with lower dislocation densities. More details on the electrical, thermal and structural characteristics of HVPE GaN and their interrelationships will be presented.

9:15 AM I9.3
CHARACTERIZATION OF HIGH-QUALITY EPITAXIAL AlN FILMS DEPOSITED BY MOVPE. Tomohiko Shibata[a,b], Keiichiro Asai, Teruyo Nagai, Shigeaki Sumiya, Mitsuhiro Tanaka and Osamu Oda[a], Hideto Miyake[b] and Kazumasa Hiramatsu[b]; [a]NGK Insulators, Ltd., Nagoya, JAPAN; [b]Mie University, Nagoya, JAPAN.

An Al-rich III-V nitride material is one of the most promising materials for future optical devices, including LEDs, LDs and photodetectors, because of its wide band gap. In a sense, AlN is a superior material in the III-V material system. Few studies have been reported on the AlN crystal characteristics because of the difficulties involved in obtaining a suitable AlN using various crystal growth techniques. However, we realized a high-quality AlN epitaxial film on a C-plane sapphire substrate by a low-pressure metal organic vapor phase epitaxy (LP-MOVPE) method. We characterized the crystal quality by X-ray diffraction, atomic force microscope (AFM) and transmission electron microscope (TEM).
C-plane AlN without any cracks was directly deposited on C-plane sapphire substrates using the raw materials of trimethylaluminum (TMA) and NH_3 by LP-MOVPE. A typical X-ray rocking curve (XRC) value of (002) AlN is 50arcsec, which is much lower than the value for GaN deposited using a conventional low-temperature buffer layer. The AlN surface is atomically smooth enough that surface atomic steps with the height of approximately 2Å, which corresponds to an AlN monolayer, can be clearly observed. Moreover, it is characteristic that the surface atomic steps are well ordered with few interruptions caused by growth pits. From TEM results, it is observed that most of the dislocations consist of edge-type dislocations that thread the surface, and that almost all screw-type dislocations disappeared at an early AlN growth stage.

9:30 AM I9.4
GROWTH OF AlN BULK CRYSTALS FROM THE VAPOR PHASE. Raoul Schlesser and Zlatko Sitar, North Carolina State Univ, Dept of Materials Science and Engineering, Raleigh, NC.

AlN single crystals were grown from the vapor phase using metallic Al or AlN powder, and nitrogen gas as precursor materials. Growth experiments were carried out under quasi-stagnant flow conditions, with typical flow rates of 100 sccm at reactor pressures ranging from 300 to 700 Torr. Growth temperatures were as high as 1900 to 2300°C. The crystal shape and fastest growth direction were found to strongly depend on growth temperature. Growth experiments that used metallic Al as a source material featured fast growth rates exceeding 10 mm/hr along the crystallographic c-axis; at relatively low temperatures (1900-2000°C) long needles were grown; temperatures around 2000°C yielded twinned platelets, while at temperatures above 2100°C c-platelets were formed. These c-plates grew at a rate of 5 mm/hr in the c-plane and 0.2 mm/hr along the c-axis. When using AlN as a source material growth rates were considerably slower, however, long-term stability of the Al flux was greatly improved. Seeded growth was demonstrated under these conditions, and crystal size was seen to linearly increase with time over several days. All grown single crystals were transparent and virtually colorless. Crystal quality was examined by a wide range of analytical techniques, including surface imaging techniques, x-ray diffraction, Raman spectroscopy, optical absorption, cathodo-luminescence and secondary ion mass spectroscopy. All analytical results indicated very high crystalline quality and purity.

9:45 AM I9.5
CRYSTALLINE AND ELECTRICAL PROPERTIES OF AlInN/GaN AND CRACK-FREE AlN/GaN SUPERLATTICES ON GaN GROWN BY METALORGANIC VAPOR PHASE EPITAXY. Shigeo Yamaguchi, Yasuo Iwamura, Kanagawa University, Dept. of Electrical, Electronic and Information Engineering, Yokohama, JAPAN; Masayoshi Kosaki, Yasuhiro Watanabe, Shingo Mochizuki, Tetsuya Nakamura, Yohei Yukawa, Shugo Nitta, Meijo University, Dept. of Electrical and Electronic Engineering, Nagoya, JAPAN; Satoshi Kamiyama, Hiroshi Amano and Isamu Akasaki, Meijo University, High-Tech Research Center and Dept. of Materials Science and Engineering, Nagoya, JAPAN.

AlN and AlInN with small In content are important materials for optical and electronic devices because of its large band offset to GaN. In spite of such attractive features, AlInN has been less studied than other III-nitride alloys principally because high-quality AlInN has been difficult to grow. For AlN/GaN, it has difficulty of easy generation of a network of cracks in AlN because of lattice and thermal expansion mismatches between AlN and GaN. We have recently succeeded in growing high-quality AlInN and AlInN/AlGaN superlattices (SLs) by optimization of growth condition, and in growing crack-free 0.5μm-thick-AlN on GaN. All samples used in this study were grown by MOVPE. A (0001) sapphire substrate was used. $Al_{0.90}In_{0.10}N$/GaN SLs or AlN/GaN SLs were grown on GaN of 2μm-thickness at 800°C or 1000°C, respectively using N_2 carrier gas. The underlying GaN was grown at 1050°C with H_2, which followed the low-temperature deposition of AlN buffer layer of 30nm. Thicknesses of AlN/GaN and $Al_{0.90}In_{0.10}N$/GaN were 1nm/5nm and 1nm/17nm, respectively. X-ray diffraction analysis of $2\theta/\omega$ scan and reciprocal space mapping revealed that AlN/GaN SLs and $Al_{0.90}In_{0.10}N$/GaN SLs were coherently grown on GaN, and satellite peaks up to over 3rd order were observed. AlN/GaN 1SL on GaN showed an electron mobility of 251 cm^2/Vs (1476 cm^2/Vs) and a sheet carrier density of 1.11×10^{13}cm^{-2} (8.03×10^{12}cm^{-2}) at 295K (at 21K). While the electron mobility gradually increased with increasing temperature, the sheet carrier density decreased. However, AlN/GaN 5SLs on GaN showed 1354 cm^2/Vs (9925 cm^2/Vs) and 1.14×10^{13}cm^{-2} (1.14×10^{13}cm^{-2}) at 295K (at 21K). In this case, the sheet carrier density remained constant. These results suggest that

crack-free AlN/GaN SLs of multiple layers grown by N_2 carrier gas has a significant potential for high electron mobility devices.

10:30 AM I9.6
IN-SITU RHEED OBSERVATION OF MOCVD-GaN FILM GROWTH.
Masatomo Sumiya, Noritaka Ogusu, and Shunro Fuke Dept. of E&E Eng., Shizuoka Univ., Hamamatsu, JAPAN.

We report the in-situ RHEED observation during the growth of GaN films by MOCVD under ~100mTorr of pressure. We have developed the MOCVD deposition system of III-V nitride semiconductor films equipped with in-situ RHEED. Since this RHEED system has the differential pumps and the screen is located in the chamber with 10cm of distance from electron gun [1], it can observe both diffraction pattern and RHEED oscillation under ~1Torr of pressure. The GaN films were deposited on sapphire substrate under 120mTorr by two-step MOCVD using TMG and NH_3 gas. The substrate was mounted on the heater unit with its face down, and the source gas was supplied with up-flow to the substrate. Although the pressure was much lower than the conventional growth condition, the epitaxial growth of GaN film was confirmed by the in-situ RHEED, and the deposition rate was estimated as 0.3μm/h. The crystallization of the LT-GaN buffer layer was observed around 900°C by the RHEED during the annealing after the deposition of the buffer layer at 600°C. The mixed RHEED pattern of GaN and sapphire was observed just before HT-GaN growth at 1000°C. The sapphire pattern disappeared after the deposition for 5min, and the streak pattern of GaN appeared. Thus, the growth mode of GaN film by MOCVD can be investigated with respect to the crystallographic point as well as GaN growth by MBE. [1] Guus J.Rijiders et.al.: Appl. Phys. Lett. 70, 1888 (1997).

10:45 AM I9.7
SURFACE ROUGHNESS AND HELICAL-TYPE GROWTH INSTABILITIES ASSOCIATED WITH EPITAXIAL GROWTH OF GaN AND InGaN THIN FILMS AT REDUCED TEMPERATURES ON GaN TEMPLATES VIA MOVPE.
Peter Miraglia, Edward Preble, Amy Roskowski, Sven Einfeldt, Robert F. Davis, Department of MS&E, North Carolina State University, Raleigh, NC.

The surface morphology of GaN(0001) and InGaN(0001) films grown at 780°C by metalorganic vapor phase epitaxy on on-axis AlN/6H-SiC(0001) substrates was investigated using atomic force microscopy. Growth was performed on conventionally and pendeo-epitaxially deposited GaN thin film templates. Instabilities in the step morphology in both film compositions, namely, the formation of hillocks and v-defects (previously associated solely with InGaN films) caused surface and interface roughening. The reduction in growth temperature and resultant reduction in surface adatom mobility had the most significant effect on the surface roughness in both GaN and InGaN films. Reduced adatom mobility increased the competition between adatom capture at step edges and clusters in the terrace region. The formation of a v-defect was linked to a step boundary dragging effect, resulting in a helical array of steps that terminate at a dislocation core of screw-type character. The $3 \times 10^9 cm^{-2}$ density of the v-shaped defects in the GaN films was similar to the dislocation density observed in these films grown in this study at 780°C. The density of these defects was reduced to $6 \times 10^8 cm^{-2}$ and $2 \times 10^8 cm^{-2}$ in GaN films subsequently grown on a GaN template layer having a thickness of 2.5μm and over the overgrown region of a GaN pendeo-epitaxy template, respectively. Films of InGaN exhibited both v-defect pit and hillock formations. Hillock formation was attributed to a transition in thermodynamic growth mode layer by layer to a three-dimensional growth of islands. A delay in the formation of v-defects in InGaN was observed and associated with ammonia partial pressure and interactions between hillock islands and screw-type dislocations.

11:00 AM I9.8
EFFECT OF Sb AND Bi IMPURITIES ON GaN GROWTH AND LATERAL EPITAXIAL OVERGROWTH BY METAL ORGANIC VAPOR PHASE EPITAXY.
L. Zhang[a], H.F. Tang[a], Z.Y. Liu[a], C.A. Paulson[a], S.E. Babcock[b] and T.F. Kuech[a]; [a]Department of Chemical Engineering; [b]Department of Materials Science and Engineering, University of Wisconsin-Madison, Madison, WI.

Isoelectronic impurities have been used to alter the surface structure and growth behavior in many compound semiconductor systems. In this study, the role and effect of antimony (Sb) and bismuth (Bi) isoelectronic centers on the structure and properties of GaN epilayers grown by metal organic vapor phase epitaxy (MOVPE) have been systematically investigated. Triethylantimony and trimethylbismuth were added into the growth ambient over a wide range of concentrations during the conventional two-step growth of GaN. The changes in microstructure were further explored by the lateral epitaxial overgrowth (LEO) technique through changes in facet formation and the lateral-to-vertical growth rates due to the presence of the dopant. Sb addition leads to improvements in the optical and structural properties of GaN epilayer, especially for the films grown under high V/III ratio conditions. During LEO, an increase in the lateral overgrowth rate of GaN is observed. Vertical facets to the LEO growth appear with the addition of Sb under conditions that normally produce triangular or sloped sidewalls over a range of growth temperatures. Bi addition leads to a decrease in surface roughness as measured by AFM. While Bi alters the growth surface, no Bi was incorporated over a broad range of gas phase concentrations as indicated by SIMS, suggesting that Bi acts as a surfactant during the GaN MOVPE growth. This interpretation is consistent with the fact that Bi has very low solubility in GaN and that the Bi distribution coefficient is estimated to be less than 0.001. The symmetrical and asymmetrical x-ray rocking curves were narrowed slightly with low Bi incorporation. Possible mechanisms on the differences in incorporation behavior between the Bi and Sb will be discussed.

11:15 AM I9.9
MEASUREMENT OF THE EFFECTIVE PIEZOELECTRIC CONSTANT OF NITRIDE THIN FILMS AND HETERO-STRUCTURES USING SCANNING FORCE MICROSCOPY.
B.J. Rodriguez, D-J. Kim, A.I. Kingon, and R.J. Nemanich, Department of Physics and Department of Materials Science and Engineering, North Carolina State University, Raleigh, NC.

The piezoelectric properties of III-V nitrides are important for new heterostructure devices. As such, measurement of the piezoelectric properties of nitride thin films and heterostructures with nanometer scale resolution is of considerable interest for determining how defects and patterned structures affect the piezoelectric response. When an electric field is applied to a piezoelectric material, it strains due to the converse piezoelectric effect. Several techniques can be used to measure these small piezoelectric displacements. The scanning force microscopy (SFM) technique is useful because the tip can be rastered to generate images of the phase and of the magnitude of the piezoelectric response in addition to being able to measure the piezoelectric displacement at single points on a sample. Another advantage of this technique is that it can resolve nanometer variation in the piezoelectric properties of a sample. Measurements can be performed by applying a voltage between a conducting tip and a bottom electrode, or between a conducting tip in contact with a top electrode and a bottom electrode. In this study, SFM is used to measure the magnitude of the effective longitudinal piezoelectric constant (d33) of AlN and GaN thin films and of AlGaN/GaN/AlN/SiC and InGaN/GaN/AlN/SiC heterostructures grown by organo-metallic vapor phase epitaxy (OMVPE) on SiC. Sputtered AlN films and films grown by molecular beam epitaxy (MBE) are also characterized. The d33 coefficients of these films are verified using an interferometric technique. Simultaneous imaging of the electrode topography, and of the phase and magnitude of the piezoelectric strain is performed. We report d33=3 pm/V for AlN/SiC and 2 pm/V for GaN/AlN/SiC.

11:30 AM I9.10
MEASUREMENT OF THE BAND OFFSET OF SiO_2 ON CLEAN GaN.
Ed Hurt, Ted Cook, K.M. Tracy, R.F. Davis, North Carolina State University, Dept of Materials Science and Engineering, Raleigh, NC; G. Lucovsky, and R.J. Nemanich, North Carolina State University, Dept of Physics, Raleigh, NC.

Oxides on GaN can be employed as a gate insulator in FET device structures or for passivation of GaN surfaces in high voltage devices. This study explores the electronic properties of the interface of SiO_2 on clean GaN. The interface formation employed a sequence that minimizes the formation gallium oxide. The GaN was grown by OMCVD on 6H-SiC (0001) with an AlN buffer layer. Prior to oxide formation the GaN surface was prepared with an ammonia chemical vapor clean at 860°C, which resulted in a clean, ordered surface. The electronic states were deduced from in situ UPS and XPS measurements. The clean surface GaN displayed band bending of 0.3 eV, while the electron affinity was measured to be 2.9 eV. A 0.4 nm layer of Si was deposited on the GaN surface via Molecular Beam Epitaxy (MBE), and the Si was oxidized by oxygen exposure and a remote O_2 plasma. This process was repeated twice with 0.2 - 0.3 nm deposition of Si and plasma oxidation. Densification of the created SiO_2 film was achieved by annealing at 650°C. UPS and XPS were recorded after each step. The results indicted a valence band offset of 2.0 eV, and a conduction band offset of 3.62 eV for the SiO_2 -GaN interface.

SESSION I10: EXTENDED DEFECTS
Chair: Richard J. Molnar
Thursday Afternoon, November 29, 2001
Room 302 (Hynes)

1:30 PM *I10.1
THEORY OF ELECTRON ENERGY LOSS SPECTROSCOPY AND

ITS APPLICATION TO THREADING EDGE DISLOCATIONS IN GaN. C.J. Fall, R. Jones, School of Physics, University of Exeter, UNITED KINGDOM; P.R. Briddon, Department of Physics, University of Newcastle upon Tyne, UNITED KINGDOM; M.I. Heggie, School of Chemistry, Physics and Enviro-Science, University of Sussex, UNITED KINGDOM.

The electronic structure of dislocations in GaN is controversial. Several experimental techniques such as carrier mobility studies and cathodoluminescence experiments have indicated that dislocations are charged while theoretical studies point to intrinsic states and/or point defect accumulation along the core as a source of electrical activity. Electron Energy Loss Spectroscopy (EELS) studies have the ability to probe the electronic structure of extended defects. Here we report first principles calculations of the EELS spectrum applied to edge dislocations in GaN. It is found that the electrostatic potential at N atoms in the vicinity of the dislocation varies by the order of a volt and casts doubt on any simple interpretation of core loss spectroscopy. On the other hand, low loss spectroscopy leads directly to detailed information about any gap states. The low loss spectrum obtained by the theory is in good agreement with recent experimental work carried out by Gutierrez-Sosa *et al* and indicates that threading dislocations in GaN possess acceptor levels in the upper half of the gap.

2:00 PM I10.2
PROFILING ELECTRIC FIELDS AROUND DISLOCATIONS IN GaN. D. Cherns and C.G. Jiao, H.H. Wills Physics Laboratory, University of Bristol, Bristol, UNITED KINGDOM.

There is evidence from transport properties, scanning capacitance microscopy and photoelectrochemical etching studies that dislocations in GaN heterostructures can be highly charged. In recent work, we have shown that this charge can be examined directly using an electron holography technique. This method, which utilizes an electron biprism in a field emission gun transmission electron microscope, compares the phase change in an electron wave incident approximately along the dislocation line direction with a nearby reference wave. Studies of edge dislocations in n-type GaN have shown a potential change of 2-3V within a few nanometers of the dislocation, consistent with a negatively charged core. A good fit to the potential profile is obtained for a line charge of 2 electrons/c, where c = 0.52nm is the unit cell spacing. In current work, the technique is being extended to dislocations of screw and mixed character, although these are more difficult owing to diffraction contrast effects and variations of foil thickness near the core. In the paper, the results will be explained, and their relevance to understanding the role of dislocations in GaN devices will be discussed.

2:15 PM I10.3
OPTICAL PROPERTIES OF GaN WITH Ga- AND N-POLARITY. M.A. Reshchikov, D. Huang, F. Yun, T. King, H. Morkoç, Dept of Electrical Engineering, Virginia Commonwealth Univ, Richmond, VA; P. Visconti, Dept of Electrical Engineering, Virginia Commonwealth Univ, Richmond, VA and Instituto per lo Studio di Nuovi Materiali per l'Elettronica, CNR, Via Arnesano, Lecce, ITALY; J. Jasinski, Z. Liliental-Weber, Lawrence Berkeley National Laboratory, Berkeley, CA.

GaN exhibits large polarization effects due to its noncentrosymmetric crystal structure. We compared photoluminescence (PL) and reflectance spectra of GaN samples with Ga and N polarities grown by molecular beam epitaxy (MBE) on sapphire substrates. Ga-polar films typically have very smooth surfaces, which are extremely difficult to etch with acids or bases. In contrast, the N-polar films have rougher surfaces and can be easily etched in hot H_3PO_4 or KOH. The quality of the X-ray diffraction spectra is also much better in case of the Ga-polar films. Surprisingly, PL efficiency is always much higher in the N-polar GaN, yet the features and shape of the PL spectra are comparable for both polarities. PL efficiency depends on concentration of nonradiative defects. Thus we conclude that, despite the excellent quality of the surface, Ga-polar GaN layers contain higher concentration of nonradiative defects. From the analysis of cross-sectional transmission electron microscopy (TEM) images, we have found that Ga-polar films have high density of threading dislocations (5×10^9 cm^{-2}) and low density of inversion domains (1×10^7 cm^{-2}). For N-polar GaN the situation is the reverse: the density of dislocations and inversion domains are 5×10^8 cm^{-2} and $\sim 1 \times 10^{11}$ cm^{-2}, respectively. One of the important conclusions derived from the combined PL and TEM study is that inversion domains do not affect the radiative efficiency, whereas dislocations reduce it significantly. Preliminary results of the reflectance and PL study demonstrate that the strains in Ga- and N-polar films grown by MBE are similar.

2:30 PM I10.4
HIGH-TEMPERATURE HARDNESS OF BULK SINGLE-CRYSTAL AlN. Ichiro Yonenaga, Institute for Materials Research, Tohoku University, Sendai, JAPAN; Andrey Nikolaev, Ioffe Institute and Crystal Growth Research Center, St. Petersburg, RUSSIA; Yuriy Melnik, Vladimir Dmitriev, TDI, Inc., Gaithersburg, MD.

Knowledge on the mechanical strength at elevated temperature is essentially important as a basis for the control of dislocation generation and plastic deformation during crystal growth and device processing. Up to now far less is known on the mechanical properties of nitride semiconductors. This paper reports on the hardness of single crystal aluminum nitride at elevated temperatures measured for the first time and compared with wide-gap semiconductors. Crack-free AlN single crystals of 0.5mm thickness were obtained from high-quality AlN thick film grown on silicon substrates by the HVPE. A Vickers indentation method was used to determine the hardness under an applied load of 0.5N in the temperature range 20 - 1400°C. The average hardness of (0001) surfaces is as 17.7 GPa at room temperature, which is harder than GaN (10.2 GPa) and sifter than 6H-SiC and Al_2O_3 (28 GPa). The fracture toughness is 0.4 $MPa{\cdot}m^{1/2}$. The hardness of GaN shows a gradual decrease from RT to 700°C, then something of a plateau in the range 700-1000°C and then a steep decrease. This temperature-dependent tendency is similar to those of GaN and 6H-SiC, which have a hcp-based structure. In the entire temperature range investigated AlN is harder than GaN but softer than SiC. The steep decrease of AlN hardness from 1000°C means the beginning of macroscopic dislocation motion and plastic deformation. Thus, it has been found that AlN has a lower susceptibility to deformation during device processing at high temperatures, similar to GaN and in contrast to Si, GaAs, and possibly other III-V compounds.

2:45 PM I10.5
INVESTIGATION OF PYRAMIDAL DEFECTS IN Mg DOPED GALLIUM NITRIDE BASED HETEROSTRUCTURES USING TRANSMISSION ELECTRON MICROSCOPY. R. Kroeger, P. Ryder, T. Boettcher, S. Figge, and D. Hommel Institute for Solid State Physics, University of Bremen, GERMANY.

The formation of pyramidal shaped defects in MOVPE grown Mg doped GaN based materials is a serious obstacle for obtaining defect free heterostructures to be used as light emitting devices in the blue spectral range. This is predominantly due to the role of these defects as non-radiating recombination centers. Since their nature is not yet well understood, a detailed study of the defect structure as well as the defect density and distribution was performed using conventional and high resolution transmission electron microscopy in plan view and cross section. An image processing program (Digital Analysis of Lattice Images, DALI) supplied information concerning the lattice distortion inside the defects. Mg doped GaN and AlGaN films of varying thickness were grown on sapphire for this study resulting in a nominal Mg concentration of about 10^{20} cm^{-3}. It was found that the c-parameter inside the defects is compressed by about four percent with respect to the matrix material. The density of defects reached values up to 10^{11} cm^{-2} and was not equal throughout layers. The defect formation started only after about 100 nm of film was already deposited. If the GaN or AlGaN layer were thick enough (more than 300 nm) several maxima of the defect density could be observed. These results point to the fact that the pyramidal defect formation is related to a yet unknown stress relaxation process due to reactions of Mg with the matrix material.

3:30 PM *I10.6
STRUCTURAL PROPERTIES AND ELECTRICAL BEHAVIOR OF GaN DISLOCATIONS. J.W.P. Hsu, Bell Labs, Lucent Technologies, Murray Hill, NJ; S.N.G. Chu, D.V. Lang, Agere Systems, Murray Hill, NJ; M.J. Manfra, L.N. Pfeiffer, Bell Labs, Lucent Technologies, Murray Hill, NJ; R.J. Molnar, Massachusetts Institute of Technology, Lincoln Laboratory, Lexington, MA; B. Heying, J.S. Speck, UCSB, Santa Barbara, CA.

The effect of dislocation type and MBE growth stoichiometry on the excess reverse bias gate leakage in GaN Schottky diodes will be presented. The samples are MBE grown GaN films on either HVPE or MOCVD templates. We show that pure screw threading dislocations are the source of reverse bias gate leakage in films grown under Ga-rich conditions. This conclusion was reached by correlating the scanning current image taken at fixed reverse biases with simultaneously acquired topographic images, and by comparing the density of leakage spots to total dislocation density and distributions of different dislocation types obtained from cross sectional TEM measurements. Pure screw dislocations consist of 30 to 50% of the total dislocations in HVPE templates while it is only a few percent in MOCVD films. Since MBE growth does not introduce new dislocations, the surface dislocation density and type distribution are determined by the template. We found the density of leakage spot is $\sim 4 \times 10^8$ cm^{-2} for HVPE template films and only 3×10^7 cm^{-2} for the MOCVD template film, while the total dislocation density is $\sim 10^9$ cm^{-2} in both cases. While dislocation type is the primary factor in determining gate leakage, growth stoichiometry is also important. The

leakage current is 2 to 3 orders of magnitude higher for samples grown under Ga-rich conditions. Nano-size Ga droplets were found at the surface terminations of pure screw dislocations in a Ga-rich film. Screw dislocations in this sample appear to have a wider and weaker contrast, and the width of their core contrast widens approaching the surface Ga droplet. In contrast, the screw dislocation line contrast remains sharp all the way to the surface in the Ga-lean sample. These results suggest that excess Ga induced changes in dislocation core structure. This in terms causes the different electrical activity associated with screw/mixed dislocations in samples grown under different conditions.

4:00 PM I10.7
CHARACTERIZATION AND LOCAL PASSIVATION OF REVERSE-BIAS CURRENT LEAKAGE PATHS IN AN AlGaN/GaN HETEROSTRUCTURE. E.J. Miller, D.M. Schaadt, E.T. Yu, University of California, San Diego, Department of Electrical and Computer Engineering, La Jolla, CA; C. Poblenz, C.R. Elsass, P. Waltereit, J.S. Speck, University of California, Santa Barbara, Materials Department, Santa Barbara, CA.

Threading dislocations present in Group III-Nitride alloys have been shown to be a major source of reverse-bias leakage current in nitride Schottky diodes, particularly those fabricated from material grown by molecular beam epitaxy (MBE). The use of nitride-based devices for low-noise and low-power applications requires minimization of this leakage current, which necessitates an understanding of and a method by which to mitigate the relevant leakage mechanisms. Using an atomic-force microscope (AFM) modified to allow measurement of local current-voltage characteristics, we demonstrate that current-induced oxidation can occur in the vicinity of dislocation-related leakage paths, resulting in a large reduction in local leakage current. By monitoring the current flowing between the tip and sample as a function of bias voltage and comparing scanning current images with topography, one can determine when leakage paths have been passivated and the amount of oxide necessary to block the current flow. Using this approach, we have found that dislocation-related current paths can be blocked up to reverse-bias voltages of 14V by current-induced formation of a 2-3nm thick oxide layer over the current path. An oxide layer is formed only where current flows between the tip and sample; detailed analysis indicates that the current flows by tunneling through the oxide layer as it grows until the oxide reaches a critical thickness, at which point the leakage path is passivated, and the current flow and oxide growth stop. Large-area diodes have been fabricated on passivated and unpassivated areas, and current-voltage characteristics for these diodes indicate that the reverse-bias current is significantly reduced by the scanning-probe-induced formation of a thin oxide layer over the leakage paths. This result suggests a variety of other treatments that could yield significant reductions in reverse-bias leakage currents in Schottky diodes fabricated from MBE-grown material.

4:15 PM I10.8
STRUCTURE AND STOICHIOMETRY OF SCREW DISLOCATIONS IN GaN: THEORY. John E. Northrup, Xerox Palo Alto Research Center, Palo Alto, CA.

There is considerable interest in determining the core reconstructions and corresponding electrical activity of the various types of threading dislocations that are present in GaN grown by MBE and MOCVD. A detailed understanding of how each type of threading dislocation affects optoelectronic properties requires knowledge of the core reconstructions and how they depend on growth conditions. In this work we present first-principles total energy calculations for possible core reconstructions of the threading screw dislocation with Burgers vector c[0001]. The relative stabilities of different core structures are calculated as a function of the chemical potentials of the atomic constituents. The calculations indicate that the core structure depends on whether growth is performed under N-rich or Ga-rich conditions. In general MBE growths (in the absence of hydrogen) will result in dislocation cores that are depleted of N. In the Ga-rich limit only Ga remains in the core, and these Ga atoms form a pair of helical chains. A dislocation with such a core is predicted to be a very strong center for nonradiative recombination. Finally, we show that a hydrogen-passivated core may become stable under experimentally accessible conditions.

4:30 PM I10.9
THICKNESS DEPENDENCE OF THE ELECTRICAL PROPERTIES OF GaN EPILAYERS. A. Castaldini, A. Cavallini and L. Polenta, INFM and Dipartimento di Fisica, Universitá di Bologna, Bologna, ITALY.

It is well assessed that thickness of gallium nitride layers is a key parameter in determining the density and the distribution of defects, especially of the extended ones. As a matter of fact, the strain related to the lattice mismatch between GaN and sapphire substrate enhances the formation of threading dislocations at the interface, consequently creating a highly defective layer. The dislocation density decreases with increasing layer thickness, because the propagation of dislocations from the interface to the top layer becomes less probable. To evidence the thickness dependence of the dislocation density, hence of the electrical characteristics, n-type HVPE GaN layers of thickness spanning from 0.8 to 61 μm have been here examined. As known, the luminescence emission characteristics are considered a sort of signature revealing the presence of extended defects, as happens about the yellow luminescence. Another very efficient method in determining carrier emission from deep levels is the spectral photocurrent analysis, where the current induced by a light beam is determined versus the light wavelength. Thus, photocurrent (PC) spectra have been collected at different temperatures to evidence the presence of emissions (blue, yellow, green and red) related to defects. Moreover EBIC (Electron Beam Induced Current) scanning microscopy analyses have been carried out in order to investigate the spatial distribution of extended defects. Finally, DLTS analyses have been performed to determine energy, capture cross section and concentration of defects. We have observed that, decreasing the thickness, the band-gap PC signal significantly increases and the broad band centered at 520 nm enhances and becomes more resolved, allowing for clearly separating green and yellow emissions. PC results have been correlated with the deep level changes achieved by DLTS.

4:45 PM I10.10
CONDUCTIVITY, PHOTOCONDUCTIVITY AND OPTICAL PROPERTIES OF AMORPHOUS GaN FILMS. Annette McIvor, Uday Lanke, Ben Ruck, Joe Trodahl, School of Chemical and Physical Sciences, Victoria University of Wellington, Wellington, NEW ZEALAND; Simon Brown, Department of Physics, University of Canterbury, Christchurch, NEW ZEALAND; Antoine Bittar, Measurement Standards Laboratory, Industrial Research Limited, Lower Hutt, NEW ZEALAND.

It has been predicted that amorphous GaN has a low density of states in the gap, and therefore has potential as a useful opto-electronic material in the blue-green spectral region. We have synthesised amorphous GaN films on various substrates by ion assisted deposition and investigated the effects of sample preparation conditions on the conducting and optical properties. The room temperature resistivity ρ_0 of stoichiometric (Ga:N of 1:1) films is above 10^5 Ω·cm, and these films exhibit a variable range hopping form for the temperature dependence of the resistivity. Films which have an excess of Ga show a much lower ρ_0 with a temperature dependence which is not consistent with variable range hopping. The optical absorption shows a band-gap of 3.1 eV, with the gap falling below that value when the amorphous network incorporates homopolar (Ga-Ga) bonds. The best films are thus transparent across the visible region with a low density of gap states, undetectable in optical absorption. The photoluminescence spectra obtained from these a-GaN films consist of a broad green light emission peaking at 500 nm. Preliminary photoconductivity measurements show high sensitivity in the UV.

SESSION I11: POSTER SESSION
Thursday Evening, November 29, 2001
8:00 PM
Exhibition Hall D (Hynes)

I11.1
PASSIVE COMPONENTS ON AlN FOR APPLICATION IN AlGaN/GaN POWER AMPLIFIERS. Bart Jacobs, Mark Kramer, Thieu Kwaspen, Fouad Karouta, Eindhoven University of Technology, Dept. of Electr. Engineering, Opto-electronic Devices Group, Eindhoven, THE NETHERLANDS; Peter de Hek, Raymond van Dijk, TNO-FEL MMIC Group, The Hague, THE NETHERLANDS.

Passive components are a very crucial part of any power amplifier. To characterize these components over a broad frequency range is important for an efficient power amplifier design. In this paper we present our recent results in the development of a library of passive components based on Coplanar Waveguide Technology. The main advantage of this technology is that it does not depend on the availability of a via-hole technique. Several different components, like transmission lines, crossings, Metal-Insulator-Metal (MIM) capacitors and NiCr resistors were measured and modelled in the 1-50 GHz range. The components were designed keeping in mind that they must be able to sustain high current densities while still having suitable electrical properties. Thick gold electroplating was used for reducing resistance and realizing air bridges. All devices were made on AlN for several reasons. This substrate material is isolating so measurements are not distorted by leakage currents. Also, this material is very suitable for use in a hybrid power amplifier. We present two de-embedding techniques to correctly determine the high frequency performance of the intrinsic device, e.g. the device without contact pads. The first technique is an extension of the Line-Reflect-Line

de-embedding algorithm. The other technique is based on ABCD parameters. This technique does not, unlike the LRL algorithm, involve a change in reference impedance. Changing to complex reference impedances can produce incorrect results when using commercial simulators.

I11.2
PRODUCTION SCALE GROWTH OF AlGaN/GaN FETS.
Shawn Gibb, David Gotthold, Chris Palmer, and Eric Armour, EMCORE Corporation, EMCORE Electronic Materials, Somerset, NJ.

AlGaN/GaN FETs have attracted a great deal of attention in recent years because of their promise for high performance RF devices and high temperature operation. However, the growth of III-Nitrides for FETs requires careful attention to, and balance between, several operating parameters. First, unlike most optical devices, these structures require high Al content layers, so understanding and control of pre-reactions is important for reproducible growth. Second, these layers must be uniform and have sharp interfaces for proper control of the piezoelectric doping. The doping is a strong function of strain, so both the Al composition and thickness must be accurately controlled. Third, a highly resistive buffer layer, with a low defect density, is required. In production scale growth there are additional concerns, including repeatability, yield (especially given the high cost of semi-insulating SiC), rapid device level testing, and ability to scale to larger wafer sizes. Before these devices can be commercialized, much work must be completed to establish a reliable and cost-effective production process while still achieving high performance. Our current material results in small scale production (on 2" sapphire substrates) include: $\mu \geq 1400$ cm^2/V·s, Ns = 0.9-1.1x10^{13} cm^{-2}, and Rs $\leq$ 500 Ω/square with $\leq$ 5% variation across the wafer and $\leq$ 1% variation from wafer to wafer. In this presentation, data on production scale material growth both on sapphire and on semi-insulating SiC substrates, in-situ monitoring, reactor design considerations, and current HFET device results, will be presented.

I11.3
OPTICAL GAIN AND STIMULATED EMISSION MECHANISMS IN InGaN GROWN BY MOCVD.
Xinhai Zhang, Soo Jin Chua, Maosheng Hao, Wei Liu, Wen Wang, Insititute of Materials Research and Engineering, SINGAPORE; Kam-Sing Wong, Hong Kong Univ of Science and Technology, Dept of Physics, Hong Kong, CHINA.

InGaN ternary alloys and related multiple quantum wells (MQWs) are attracting much interest because they serve as the active region in blue light emitting diodes (LEDs) and blue laser diodes. Despite a lot of progress being made in device applications, the optical gain and stimulated emission mechanisms in these materials are still not well understood. In this paper, optical pumping measurements are used to study the optical gain and stimulated emission (SE) mechanisms in InGaN epilayers and InGaN/InGaN MQWs. The InGaN epilayers and InGaN/InGaN MQWs used in this study were grown by metalorganic vapor deposition (MOCVD) on (0001) sapphire substrates. The optical pumping measurements were performed at room temperature. Under low excitation intensity, only spontaneous emission was observed. Above certain threshold intensity, stimulated emission (SE) appears on the high-energy side of the spontaneous emission spectrum. With further increase of the excitation intensity, the SE becomes stronger and stronger, and dominates the emission spectrum. The red shift of SE was observed with further increase in excitation power, due to the band gap renormalization. Our results showed that the spontaneous emission is due to the recombination of localized states, while the SE comes from the extended states. Our results suggest that the localized states are unwelcome to the lasing emission in these materials, although these localized states benefit InGaN blue and green LEDs.

I11.4
CHANNELED IMPLANTATION OF Zn INTO GaN: INDUCED DAMAGE AND LATTICE EXPANSION.
F.-R. Ding, Instituut voor Kern-en Stralingsfysica, Catholic University of Leuven, BELGIUM and Department of Technical Physics, Peking University, Beijing, CHINA; A. Vantomme, B. Pipeleers, Instituut voor Kern-en Stralingsfysica, Catholic University of Leuven, BELGIUM; K. Jacobs, I. Moerman, University of Gent-IMEC, BELGIUM; K. Iakoubovskii, G.J. Adriaenssens, Laboratorium voor Halfgeleiderfysica, Catholic University of Leuven, BELGIUM.

Rutherford backscattering and channelling spectrometry (RBS/C) and high resolution X-ray diffraction (XRD) were used to investigate the damage and the lattice expansion in GaN after *channeled* implantation with Zn at room temperature, using an energy of 140keV and a dose range from 1x10^{13}/cm^2 to 4x10^{16}/cm^2. Two damage regimes are observed after implantation: one at the surface and another at a depth roughly corresponding to the projected range. The damage level is very small at doses below 2x10^{14}/cm^2 and then gradually rises with increasing dose; the backscattering yield from the near surface region reaches the random level at doses higher than 2x10^{16}/cm^2 and then extends deeper into the sample. Finally, a completely damaged (i.e. amorphous) surface layer and a highly defective deeper layer are formed. The lattice expansion calculated from (0002) and (0004) X-ray diffractions of GaN after *channeled* implantation exhibits three dose dependence regimes: the perpendicular lattice parameter initially increases with dose, subsequently varies slowly in an intermediate dose range, and diminishes at very high doses. This variation of lattice expansion is attributed to the competition between the defect creation and the defect interactions, such as annihilation and clustering of defects; and strain relaxation by amorphization occurring in the implanted layer. Photoluminescence measurements after an RTA treatment at 1100°C for 30 seconds in flowing N_2 reveal a blue Zn related luminescence line with a dose depending intensity.

I11.5
TRIANGULAR QUANTUM WELL FOR III-V NITRIDE LIGHT-EMITTING DIODES.
R.J. Choi, S.M. Jeong, M.G. Cheong, H.S. Yoon, E.-K. Suh, H.J. Lee, Chonbuk National Univ, Dept of Semiconductor Science and Technology and Semiconductor Physics Research Center, Chonju, KOREA.

III-V Nitride light-emitting diodes (LEDs) have been fabricated by adopting triangular quantum well structure in the active layer. By controlling the potential slope, both electrons and holes may be restricted in a narrow, two-dimensional region in the quantum well. This localization of carriers may also obviate the parasitic piezo-electric field in the well due to lattice mismatch between the well and barrier components. Furthermore, the non-radiative recombination can be suppressed because of the potential slope. These have been proved by fabricating the quantum well and LED structures in which photoluminescence intensities are greatly enhanced with reduced linewidths. Various phenomena observed in the triangular quantum wells will be discussed.

I11.6
PULSED MEASUREMENTS ON PASSIVATED AND UNPASSIVATED AlGaN/GaN HEMTS.
Bart Jacobs, Mark Kramer, Thieu Kwaspen, Fouad Karouta, Eindhoven University of Technology, Dept. of Electr. Engineering, Opto-electronic Devices Group, Eindhoven, THE NETHERLANDS; Peter de Hek, Raymond van Dijk, TNO-FEL MMIC Group, The Hague, THE NETHERLANDS.

One of the most important problems to be tackled in high power amplifiers based on AlGaN/GaN HEMTs is the reduction of current dispersion. Dispersion is assumed to be related to traps present in the AlGaN/GaN material or traps located at the AlGaN surface or both. A difficulty in analysing this effect is the difference in time constants that govern this phenomenon. In this paper we present our results on our recent efforts to reduce this dispersion. The investigations were carried out on an undoped HEMT structure and a structure that had a doped donor layer. We used PECVD SiNx layers with varying thicknesses and layers that were deposited using different SiH4/NH3 ratios. The dispersion was measured before and after nitride deposition using pulsed measurements with pulse widths ranging from the ms to us range. Furthermore, a function generator was used to investigate output wave shapes up to 3 MHz. The opening of the SiNx layer was done using an Ar/SF6 plasma in a standard Reactive Ion Etcher (RIE). Prior to deposition several chemical treatments were used like diluted ammonia and hydrochloric acid. A two-finger U-shape HEMT layout was used. The dispersion was determined as a function of several geometrical dimensions like the gate-source spacing, gate-drain spacing, gate length and width. In addition to the change in transistor performance, like the small-signal characteristics and load-pull performance, we looked at the changes in sheet carrier density and changes in the behavior of ohmic and Schottky contacts.

I11.7
CHARACTERIZATION OF GALLIUM NITRIDE WAVEGUIDES.
J.F. Muth, G.J. Rasmussen, J.C. Roberts, Electrical and Computer Engineering Dept., North Carolina State University, Raleigh, NC.

GaN is an interesting and useful material for optoelectronic devices with blue lasers, LEDs, and ultraviolet photodetectors now in commercial production. This study investigates the optical characteristics of GaN on sapphire waveguides. The waveguides were grown by MOCVD on c-plane sapphire. The high index GaN on lower index sapphire form a natural planar waveguide. Ridge and channel waveguides were formed by reactive ion etching and over coating with silicon dioxide. The end facets of the waveguides were polished allowing laser light at telecommunications and visible wavelengths to be end-fire coupled into the waveguides. Modal patterns were observed using a camera. The insertion loss and scattering loss mechanisms will be discussed.

I11.8
ELECTRICAL AND OPTICAL STUDIES OF THE ORGANIC LIGHT EMITTING DEVICES USING GaN-POLYMER NANOCOMPOSITES.
Moonhee Kim, Jae-Yoo Kim, Jong-Ho Choi, Dept. of Chemistry, Korea University, Seoul, KOREA.

Organic light emitting devices (OLEDs) with the structure of ITO-coated glass/GaN (quantum dots or nanowires)-PVK nanocomposite/DCM-doped Alq_3/Li:Al were fabricated and characterized. GaN nanocrystals were synthesized by the laser ablation method and dispersed in the hole conducting PVK polymer as a dopant. The nanocomposite was spin-coated on the ITO-coated glass and then DCM-doped Alq_3 was deposited by the cluster beam deposition (CBD) methods. The device properties such as photoluminescence, electroluminescence, external quantum efficiencies, and I-V characteristics were examined. For the devices with GaN nanocrystals the external quantum efficiencies were significantly improved compared to the devices without nanocrystals.

I11.9
Abstract Withdrawn.

I11.10
ELECTRICAL PROPERTIES AND INTERFACIAL REACTIONS OF Pd/Ni/Au OHMIC CONTACTS TO SURFACE TREATED P-GaN.
June-O Song, Ja-Soon Jang, Dong-Jun Kim, Seong-Ju Park, Tae-Yeon Seong, Kwangju Inst of Sci & Technol, Dept of Materials Science & Engineering, Kwangju, KOREA.

We investigate the electrical properties and the interfacial reactions of Pd/Ni/Au ohmic contacts to p-GaN(n_a = $3\text{x}10^{17}$ cm^{-3}), which was two-step surface-treated using KOH, buffer oxide etch (BOE), $(NH_4)_2S_x$, and t-Butyl alcohol-$(NH_4)_2S_x$ solutions. The Pd (20 nm)/Ni (30 nm)/Au (80 nm) films were deposited on the surface-treated p-GaN by electron beam evaporation. Some of the contacts were rapid-thermal-annealed in a N2 ambient at temperatures in the range of 400 - 600°C. The current-voltage (I-V) measurements show that the as-deposited contacts produce a specific contact resistance in the range of $7\text{x}10^{-2}$ - $2\text{x}10^{-3}$ Ωcm^{-2}. It is, however, shown that annealing of the contacts influences the specific contact resistance, namely, it varies from $\sim10^{-1}$ to $\sim10^{-5}$ Ωcm^{-2}, depending on the surface treated conditions. Effective Schottky barrier heights (SBHs) of the contacts are determined using Norde and I-V-T methods. It is shown that the SBHs are dependent on the surface-treatments and annealing temperatures. Auger depth profiling, I-V-T measurements, and X-ray photoemission spectroscopy are carried out to investigate interfacial reactions and current flow mechanisms, and hence ohmic mechanisms.

I11.11
ANALYSES OF PERFORMANCE FOR CONVENTIONAL AND FINGER-TYPE GaN-BASED LIGHT EMITTING DEVICES.
Chii-Chang Chen, Yi-Sheng Ting, Gou-Chung Chi, Dept of Physics, National Central Univ, TAIWAN; Jung-Tsung Hsu, Opto-Electronics & Systems Laboratories, Industrial Technology Research Institute, Chutung, TAIWAN.

The one of the problems for the conventional GaN-based LED is the current crowding under the area of the p-type electrodes near the n-type electrodes. This is due to the fact that the maximum electric field under the coplanar electrodes such as the electrode structure in GaN-based LED occurs at the edge of the electrodes and leads to decrease the emission efficiency of the devices. The higher quantum efficiency of the large-scale GaN-based LED with finger-type electrodes proposed by Lumileds Lighting has been demonstrated than the conventional LED. However, the width of the p-type electrode for the finger-type LED is still not optimized. In this work, the electric field under the p-type electrodes has been theoretically studied to analyze the electrical properties of the conventional and finger-type GaN-based LED's. The width of the p-type electrode to have the minimum power consummation for the finger-type LED is 70um. For the same chip size of 310umx310um, the power consummation of the conventional LED has been calculated about 1.5 times than the finger-type one leading to more heating and lower emission efficiency in the conventional LED.

I11.12
REVERSE-ANNEALING PHENOMENON DURING THE HIGH-TEMPERATURE IMPLANTATION OF Ar IONS INTO GaN FILMS.
Igor Usov, Nalin Parikh, Curriculum in Applied and Materials Sciences, Univ of North Carolina, Chapel Hill, NC; Darren Thomson, Robert Davis, Dept of Materials Science and Engineering, North Carolina State University, Raleigh, NC.

A systematic investigation of the damage accumulation in GaN films induced by 150keV Ar ions as a function of implantation temperature and dose rate has been conducted. The depth distribution of the disorder in the Ga sublattice has been measured by RBS/channeling spectrometry with a glancing angle detector geometry to provide enhanced depth resolution. Two disordered regions were identified in the damage depth distribution: a near-surface peak and a bulk damage peak corresponding to the maximum of the nuclear energy loss. These regions exhibited different behavior as a function of implantation temperature. The height of the near-surface peak, as expected, decreased with implantation temperature approaching the magnitude of the unimplanted sample. The displaced atomic density in the bulk damage peak induced by Ar ions implanted to a dose 3×10^{15} cm^{-2} at the dose rate $0.45\mu A/cm^2$ also followed this tendency and decreased in the temperature range from room temperature to 500°C. The implantation at higher temperatures resulted in an increase in the amount of damage, reaching a maximum at about 700°C and displayed a characteristic "reverse annealing" behavior. Further increase of the implantation temperature to 1000°C reduced the disorder. The influence of the dose rate and implantation temperature on the radiation damage accumulation will be discussed. It is suggested that the "reverse annealing" in the backscattering yield is due to the formation of secondary defects involving Ga atoms.

I11.13
EVALUATION OF (In,Ga)N FILMS AS OPTICAL ABSORPTION FILTERS FOR APPLICATION IN INTEGRATED FLUORESCENCE DETECTION MICRO-BIOANALYTICAL SYSTEMS.
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Quantitatively accurate fluorescence detection in integrated micro-bioanalytical systems requires the selective exclusion of light from the excitation source (typically blue or uv) and transmission of the longer wavelength fluorescence signal. In the present research, the application of (In,Ga)N alloy thin films as optical filters for absorption of blue (470 nm) and transmission of green (530 nm) is being evaluated. RBS, PL, XRD, and absorption spectra are presented for (In,Ga)N thin films grown by MOCVD on sapphire substrates with 4 μm GaN buffer layers. As the InN mole fraction is increased from 5 to 9%, modeling results suggest that the absorption edge should broaden by about 45 meV, in good agreement with the absorption data, which gave a value of 40 meV. The model further suggests that a 9 μm film with 9% InN would transmit approximately 50% of the green light and 2 x 10^{-6}% of blue light, a transmission ratio of 2.5 x 10^7. For a filter application, it is also important that photoluminescence be effectively suppressed. Thus, phase separation must be avoided, and defects that absorb nonradiatively without significantly broadening the absorption edge must be selectively introduced. The performance tradeoffs that guide the engineering of defects in these (In,Ga)N filters will be discussed. The authors from UC Berkeley acknowledge the support of NSF (DMI-0088145), and the NSF Graduate Research Fellowship Program.

I11.14
THE MECHANISM OF Ti/Al/Ni/Au OHMIC CONTACT ON AlGaN/GaN HETEROSTRUCTURE FIELD EFFECT TRANSISTOR.
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Reducing specific contact resistivity of Ohmic contacts is important in the performance of AlGaN/GaN heterostructure field effect transistor (HFET). In the previously reported results, Ohmic contact on AlGaN/GaN HFET was widely used Ti/Al based electrode. It is suggested that in Ti/Al based multi-layer contact to HFET, low resistance Ohmic contact can be achieved by the creation of N vacancies, acting as a n-type donor with high temperature annealing. The minimum specific contact resisvity of Ti/Al Ohmic contact was $10^{-4}\Omega cm^2$ on undoped AlGaN. And the contact resisvity of Ti/Al/Ni/Au Ohmic contact was lower than that of Ti/Al Ohmic contact. However the effect of Ni/Au over layer on the reduction of contact resistivity were still unclear. In the present work, Ohmic contact with low contact resistivity on undoped AlGaN was obtained by optimum rate of over layer thickness. When the over layer thickness of Ni/Au was 40/50nm, the minimum contact resistivity $8.43\times10^{-6}\Omega cm^2$ was obtained after annealing at 500°C. In order to investigate the Ohmic mechanism, XRD, HRTEM, and secondary ion mass spectroscopy (SIMS) were employed. The HRTEM analysis showed that $AlTi_XN$, TiN and Al_3Ti were formed below the metal contact. Nitrogen vacancies acting as donor were generated by these inter-metallic alloys and electron concentration increased at the interface of metal with AlGaN. This suggests that Ni-Au-Al alloys formed between Ti/Al and Ni/Au after annealing, protecting the

inter-diffusion of oxygen atoms. This leads to the reaction of Al and Ti atoms with nitrogen ones at 500°C without oxidation, resulting on the decrease of contact resistivity compared to Ti/Al Ohmic contact. From SIMS analysis, metal, gallium, nitrogen and oxygen distribution will be obtained from the compositional depth profile. From these analysises, the mechanism of Ti/Al/Ni/Au Ohmic contact on AlGaN will be proposed.

I11.15
Abstract Withdrawn.

I11.16
ELECTRICAL PROPERTIES OF GAaN/InGaN MQW HETEROJUNCTION DIODES AS AFFECTED BY VARIOUS PLASMA TREATMENTS. J. Kim, B. Luo, R. Mehandru, F. Ren, Department of Chemical Engineering, University of Florida, Gainesville FL; K.P. Lee, S.J. Pearton, Department of MS&E, University of Florida, Gainesville, FL; A.Y. Polyakov, N.B. Smirnov, Institute of Rare Metals, Moscow, RUSSIA; A.V. Osinsky, Corning Applied Technologies, Woburn, MA.

p-GaN/p-AlGaN/InGaN MQW/n-AlGaN/n-GaN structures grown on sapphire were processed into mesa diodes by dry etching in Ar/Cl plasma. Reverse current and series resistance of such diodes were studied as a function of various plasma treatments: treatment in ozone, in nitrogen, in deuterium, in air. It is shown that optimal results in terms of the lowest reverse current and lowest series resistance are produced by short (5 min) treatment in ozone. Increasing the time of ozone treatment or mixing ozone treatment with other plasma treatments led to serious surface damage compromising the performance. The amount of surface damage was found to be the highest for nitrogen plasma treatment. In the case of D plasma some passivation of acceptors some passivation of acceptors was apparent and led to poor electrical properties. For the samples prepared by ozone treatment we'll also present the results of C-V profiling, admittance spectroscopy and DLTS measurements.

I11.17
ELECTRICAL PROPERTIES OF n-GaN/p-SiC AND n-AlGaN/p-SiC HETEROJUNCTION DIODES. B. Luo, J. Kim, R. Mehandru, F. Ren, Department of Chemical Engineering, University of Florida, Gainesville, FL; K.P. Lee, S.J. Pearton, Department of Materials Science and Engineering, University of Florida, Gainesville, FL; A.Y. Polyakov, N.B. Smirnov, A.V. Govorkov, Institute of Rare Metals, Moscow, RUSSIA; A.V. Osinsky, Corning Applied Technologies, Woburn, MA.

Electrical properties of n-GaN/p-SiC and n-AlGaN/p-SiC heterojunction diodes were studied in a wide range of temperatures. It is shown that the leakage current is more than an order of magnitude lower in n-AlGaN/p-SiC diodes compared to n-GaN/p-SiC diodes. The I-V characteristics in the forward direction indicated a serious impact of tunneling (the apparent ideality factor of about 4 was found at room temperature). The breakdown voltage of n-GaN/p-SiC decreased from 2V to 0.5V when the measurement temperature was increased from 300K to 573K. Similar increase in temperature changed the breakdown voltage of n-AlGaN/p-SiC structures from 4.5V to 2V. This difference in electrical properties is most likely caused by the improved quality of the AlGaN/SiC interface compared to the GaN/SiC interface as indicated by EBIC and MCL studies on these structures.

I11.18
GROWTH OF HIGH Al CONCENTRATION AlGaN FOR SOLAR BLIND PHOTODETECTOR APPLICATION. Shiping Guo, Milan Pophristic, Trina Jarvis, Ian Ferguson, EMCORE Corporation, Somerset, NJ.

To date, the growth for AlGaN has focused on lower aluminum concentration materials for FET, visible LD and LED applications with some recent research in higher aluminum concentration materials (40-60% Al) for solar blind detectors (SBD) and UV LEDs. However, little is known about the growth of these materials and their physical properties. In this work a new design growth chamber, optimized for the AlGaN growth, was utilized. The vapor solid distribution coefficient was found to be approximately unity for Al. Crack free AlGaN films of 40%-60% Al with thickness of 0.5 μm were achieved. Room temperature Hall measurements have shown a carrier concentration of ~1E18 cm^{-3} and mobility of 35 cm^2 /Vs for n-type Si doped AlGaN epilayers with ~40% Al. A narrow Si doping window was obtained compared to that of Si doping in GaN. SIMS measurements show low C and O background doping levels at low 10E16 cm^{-3}. Sharp band edge absorption was observed by PE transmission measurements. AlGaN based p-n and p-i-n SBD structures were grown and typical diode I-V curves were observed. A strong correlation between the material quality and the characteristics of devices such as SBD photodetectors was obtained. The growth of high quality InAlGaN alloys with high Al concentration was also explored.

I11.19
ULTRAVIOLET AlGaN-BASED PHOTODETECTORS GROWN BY GAS SOURCE MOLECULAR BEAM EPITAXY WITH AMMONIA. Vladimir Kuryatkov, Gela Kipshidze, Boris Borisov, Sergey Nikishin, Henryk Temkin, Texas Tech Univ, Dept of Electrical and Computer Engineering, Lubbock, TX; Mark Holtz, Texas Tech Univ, Dept of Physics, Texas Tech Univ, Lubbock, TX; Peter Deelman, California Inst of Technology, Jet Propulsion Lab, Pasadena, CA.

We describe the growth procedures used to prepare high quality Schottky barriers of AlGaN. These Schottky barriers are used to fabricate photodetectors operating between 220 and 350 nm for applications requiring both broad and narrow spectral response and front-surface illumination. Detector structures were grown on 2-inch silicon and sapphire substrates by gas source molecular beam epitaxy with ammonia. Typical structures consisted of a 40 nm AlN buffer layer and the active AlGaN layer. Layers of n-AlGaN, with AlN mole fraction varied between 0.05 to 0.50, were grown at a temperature of 800-830°C on the AlN buffer layer. The AlGaN thickness was ~1μm. AlGaN composition was estimated from cathodoluminescence and optical reflectance measurements. The long-wavelength cutoff of the detector is determined by the composition of the AlGaN surface layer. Free carrier concentrations in AlGaN were found to be in the $(0.1\text{-}1.0)\times10^{18}$ cm^{-3} range using capacitance-voltage measurements. Ni, Au, and Pt were used to form Schottky barriers with diameters ranging from 50 to 500μm. Ti/Al/Ni/Au was used as an Ohmic contact. The Schottky diodes have a leakage current as low as 1 pA at zero bias and 1μmA at -10 V bias. The influence of geometry and structure on the spectral response and noise characteristics of these Schottky diodes will be discussed.

I11.20
SYNCHROTRON RADIATION PHOTOEMISSION SPECTROSCOPY STUDY OF Pt TRANSPARENT OHMIC CONTACTS ON P-TYPE GaN DURING ANNEALING.
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Pt-based contacts are promising candidate for ohmic contacts on p-type GaN due to its low contact resistivity and high light transparency. During annealing, the electrical properties of Pt contact could be changed due to the outdiffusion of Ga or N atoms into metal. Furthermore, strains introduced in GaN and Pt contact due to lattice mismatch could affect the electrical properties of Pt contact. However, no work was conducted experimentally on this. In the present work, effect of thermal annealing on the electrical properties of Pt ohmic contact on p-GaN was investigated by measuring the strain of Pt layer and surface Fermi level with annealing temperature. On p- GaN films grown by MOCVD, Pt (100 Å) was deposited and annealed at temperature of 200 ~ 450°C for 1 min. The change of contact resistivity was monitored using transfer length method. Simultaneously, X-ray diffraction and synchrotron radiation photoemission spectroscopy analysis were performed to examine elemental diffusion, and resultant change of microstructure and surface Fermi level movement with annealing temperature. The contact resistivity gradually decreased from 1.4×10^{-3} to 1.3×10^{-4} Ωcm^2 with annealing temperature. In the XRD analysis, epitaxial relationships of Pt(111)//GaN(0001) and Pt[110]//GaN[1120] were observed with compressive strain of ~1% in the as-deposited state. The strain was relaxed and the relative ratio of Ga/N increased gradually and the surface band bending decreased by 0.3 eV as annealing temperature increased up to 450°C indicating that Ga atoms outdiffused into the Pt layer. The decrease of contact resistivity could be attributed to the outdiffusion of Ga atoms into Pt layer leaving Ga vacancies at the subsurface of GaN. Moreover, the compressive strain at the surface of p-GaN was relaxed through annealing, resulting in the decrease of the Schottky barrier height leading to the reduction of the contact resistivity.

I11.21
DAMAGE STUDY OF Er-IMPLANTED GaN. Bert Pipeleers, Susan M. Hogg, André Vantomme, Inst voor Kern-en Stralingsfysica, Catholic University of Leuven, Leuven, BELGIUM; Koen Jacobs, Ingrid Moerman, University of Ghent, Ghent, BELGIUM.

Doping of GaN with Er by implantation will create significant lattice damage in the semiconductor lattice, which can be detrimental for its optical and electric properties. Rutherford backscattering and channeling spectrometry (RBS/C) and high resolution X-ray

diffraction (HRXRD) are used to investigate the influence of implantation dose, temperature and geometry on the generation of defects. Er-ions are implanted at 80 keV and 170 keV, using doses between 7.5x10^{13} and 1.2x10^{15} at/cm^2 at temperatures from room temperature to 450°C. From RBS spectra of the 80 keV and 170 keV room temperature implanted samples, an increasing defect density with increasing dose is observed for random implantation (i.e. with the GaN c-axis tilted 10° away from the ion beam). For channelled implantations, where the ion beam is aligned with the c-axis, the damage is reduced significantly. Secondly, raising the temperature will recover created defects instantaneously. In particular, for random implantations there will be less defects retained after implantation at higher temperatures. Due to the larger projected range of the 170 keV implantations two distinguishable damage regions can be revealed: one at the surface and the second at the end of range. This phenomenon is observed both for random as well as for channeled implantation, although the latter geometry results in a significantly deeper ion (hence defect) distribution. Implanting Er-ions, which are bigger then Ga-atoms, will stretch the GaN lattice. This conclusion can be deduced from the XRD results, where the Er-doped layer has a slightly larger perpendicular lattice parameter compared to the undamaged GaN. At very high doses, gradual amorphisation of the GaN causes this effect to disappear. After annealing at a temperature of 950°C the lower defect concentration retained when using channeled implantation results in green Er-related luminescence.

I11.22
PHOTOELECTROCHEMICAL OXIDATION OF GaN EPILAYERS.
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GaN epilayers grown by molecular beam epitaxy were oxidized by photoelectrochemical (PEC) processing in KOH solutions. The samples were characterized by extrinsic photoconductivity, photoluminescence (PL), and Raman scattering. The oxidation was found to reduce the photoconductivity and concentration of deep level states in comparison with the as-grown sample. The emission due to donor-bound exciton was enhanced while the PL band at 3.4 eV was suppressed by the oxidation. This band is related to structural defects. Negligible strain was observed in the oxidized epilayers. Metal-oxide-semiconductor (MOS) capacitors were fabricated by using the PEC-formed Ga oxide. Capacitance-voltage measurement showed the electric properties of the MOS structures to be dependent on the oxide thickness and post-treatment. Thin oxide exhibits high capacitance and reverse leakage, which can be reduced by rapid thermal annealing (RTA). Thicker oxide layers exhibit improved electrical properties. The results show the possibility to obtain low density of interface states in PEC-grown Ga-oxide/GaN structures.

I11.23
LOW-RESISTANCE OHMIC CONTACTS ON P-TYPE GaN USING Be IMPLANTATION.
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Implanted ohmic contacts were made on metalorgnic chemical vapor deposition grown p-type GaN. Before implantation, 2500A SiO_2 layer was deposited on Mg-doped GaN samples by thermal coator. 9Be was implanted with dosages of (11013 11015)cm^{-2} at an energy of 30KeV to decrease the contact resistance of the metal contact, followed by wet etching process to remove SiO_2 layer. All implanted samples were activated by RTA-annealed at 11000C for 30 seconds. The annealed samples were deposited with Ni(20nm)/Au(100nm) and then alloyed at different annealing temperature ranging from 400-5500C for 5 minutes. Four-probe measurements were performed on transmission-line model patterns. The apparent specific contact resistance of Be-implanted GaN was about 110-5[cm^2.

I11.24
HIGH EFFICIENCY UV-EMISSION AT 345 nm FROM InAlGaN LIGHT-EMITTING DIODES.
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Single peaked and high efficiency ultraviolet (UV) emission at 345 nm from InAlGaN light-emitting diodes (LEDs) is demonstrated under continuous current injection conditions. III-nitrides are currently of great interest for application to UV laser-diodes and LEDs. We have already revealed that InAlGaN alloy shows high photoluminescence intensity at room temperature in the UV range (300 - 350 nm). In this report, we investigated optical and electrical properties of bulk InAlGaN UV-LEDs working at 345 nm. The LED samples were grown at 76 Torr on the Si-face of on-axis SiC (0001) substrates by a metalorganic vapor phase epitaxy (MOVPE). The structure consists of a 600 nm-thick Si-doped $Al_{0.18}Ga_{0.82}N$ buffer layer grown on the substrate, 80 nm-thick $In_{0.05}Al_{0.34}Ga_{0.61}N$ active layer and 600 nm-thick p-$Al_{0.18}Ga_{0.82}N$ layer with 20 nm-thick p-GaN capping layer. The growth temperature of the AlGaN n-type layer, the InAlGaN active layer and AlGaN and GaN p-type layers were 1100°C, 750°C and 1050°C, respectively. After the growth, the LED samples were annealed at 750°C under flowing nitrogen (760 Torr) to activate the Mg acceptors. Ni/Au was used for the p, n-type electrode. The electroluminescence (EL) measurements were performed at room temperature under a continuous current injection conditions. The luminescence spectra were detected by a charge-coupled device system. The single and high efficiency emission peaked at 345 nm was observed under injected current density from 0.03 to 0.16 kA/cm^2. Any significant broadening and peak shift of the EL spectrum were not observed throughout the whole range of the injected current density. This would be a significant result for development of the InAlGaN based UV-emitters.

I11.25
STUDY OF ENERGY RELAXATION AND HEAT FLOW IN GaN AND GaN/AlGaN HETEROSTRUCTURES USING THERMAL NOISE MEASUREMENTS.
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We have studied electric field induced heating of electrons in bulk GaN and GaN/AlGaN heterostructures with a two-dimensional electron gas (2DEG) using thermal noise measurements. The structures are grown on sapphire by molecular beam epitaxy. The structure with a 2DEG had a carrier density, n= 1.14×10^{13} cm^{-2}, and mobility, μ = 676 cm^2/V s, at room temperature as determined from Hall measurements. Noise measurements were performed for different bias currents at frequencies up to 100 KHz on 500 μm long and 20 to 50 μm wide wire structures. Both in bulk GaN and GaN/AlGaN samples the excess noise power was found to have a 1/f–like frequency–dependent component at low frequencies and a frequency–independent component at high frequencies. The excess noise power scalesquadratically with the bias current. The electron temperature was extracted from the frequency–independent component of excess noise. In the presence of bias current, the electron temperature depends on energy relaxation of electrons via phonon emission as well as thermal boundary resistance between the GaN and sapphire.

I11.26
INVESTIGATIONS ON AlGaN:Mg CLADDING LAYERS IN LASER STRUCTURES.
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AlGaN is commonly used for cladding layers in GaN laser structures, but due to the tensile biaxial strain state of AlGaN grown on GaN, these layers tend to release the strain energy by the formation of cracks. AlGaN/GaN strained-layer superlattices (SLS) are seen as a potential way to extend the range of possible Al concentrations. But one major drawback of these highly p-doped SLS is the formation of a 2D-hole gas, which leads to an anisotropy of conductance and therefore to current spreading in laser structures, reducing the effective current density in the active region.
GaN laser structures with AlGaN SLS and bulk cladding layers have been grown by metal organic vapor phase epitaxy (MOVPE) onto sapphire. The extent of current spreading has been investigated in view of doping level and selective doping of SLS barriers and wells. The samples have been processed as gain-guided laser structures with different stripe widths for the p-contact opening and were characterised electro-optically in LED mode. Structures with SLS as cladding layers showed only a weak influence of the stripe width on the serial resistance and the quantum efficiency of the devices, which points towards significant current spreading. In comparison samples are investigated which were processed with a ridge waveguide structure.
For a quantitative understanding Hall measurements were carried out on Mg-doped SLS grown by MOVPE on top of semiinsulating GaN, showing an increase in lateral hole mobility by a factor of 4 compared to AlGaN bulk layers with the same average Al content. Based on this a 2D model of GaN laser structures has been developed to estimate the influence of current spreading. The model will be used to discuss the electro-optical properties of the structures.

I11.27
SELECTIVE HYDROGEN SENSORS BASED ON Pd/AlN/Si -MIS DEVICE STRUCTURE.
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and Computer Engineering; S. Flaminia, Ford Motor Company; G.W. Auner, L. Rimai, P. Siy, Department of Electrical and Computer Engineering; S. Ng, Department of Chemical Engineering and Material Science; R. Naik, Department of Physics and Astronomy, Wayne State University, Detroit, MI.

Detection of hydrogen is of paramount importance in all hydrogen applications. The sensing device should be sensitive as well as selective for a better performance. An array of Pd/AlN/Si metal-insulator-semiconductor (MIS) devices has been developed using plasma source molecular beam epitaxy (PSMBE) technology for deposition of AlN on Silicon and magnetron sputtering for deposition of palladium electrodes (via mask) on AlN. The C-V characteristic of the device shows a clear shift in the presence of hydrogen. The sensors were characterized using C(V) and C(t) measurements under varying hydrogen flow rate and hydrogen concentration. The effects of oxygen and hydrocarbon gases on the sensor were also studied. The device responds selectively to hydrogen. Reference electrodes with aluminum were also deposited adjacent to Pd on the same substrate for improved electronic packaging. The results of testing of the device with reference electrode will be presented

I11.28
Abstract Withdrawn.

I11.29
EFFECT OF Ge IN Cl_2 PLASMA FOR REACTIVE ION ETCHING OF GaN. Tatsuhiro Urushido, Harumasa Yoshida, Hideto Miyake, Kazumasa Hiramatsu, Mie University, Department of Electrical and Electronic Engineering, Mie, JAPAN.

Reactive ion etching (RIE) techniques with Cl_2 based gases are generally used for fabrication of GaN based III-nitride semiconductors. It was reported that smooth surface of the etched GaN was obtained by RIE using $SiCl_4$ plasma[1]. We found that the Ge in Cl_2 plasma for RIE of GaN plays an important role to obtain smooth GaN etched surface. The GaN layer was grown by MOVPE on buffer layer deposited at low temperature on (0001) sapphire substrate. SiO_2 stripe mask of 5μm width with a periodicity of 10μm were patterned by conventional photolithography. The Ge plates of 3.4-23.8 cm^2 were placed between the GaN substrate and 6 inch-quartz tray which covered cathode in the RIE chamber. We investigated the effect of not only Ge but also Si for the comparison under the same condition. Smooth surfaces were obtained for both Ge and Si, and the etch rate of 0.6 μm/min for Ge was higher than that of 0.4 μm/min for Si. Optical emission spectroscopy revealed broad-band optical emissions from 300 nm to 550 nm, which are related to the generation of $GeCl_x$ ions and radicals for Ge in Cl_2 plasma. However, a rough surface with GaN whiskers was formed for the quartz tray without Ge or Si. These results suggest that high energy Cl^+ ion gives severe damage to the GaN surface. Therefore, the smooth surface of etched GaN is obtained by the effect of Ge in Cl_2 plasma. [1] I. Adesida et al. : Appl. Phys. Lett. 63 (1993) 2777.

I11.30
ELECTRICAL CHARACTERIZATION OF MgO/GaN AS MOS STRUCTURES. J. Kim, R. Mehandru, J.W. Johnson, B. Luo, F. Ren, Department of Chemical Engineering, University of Florida, Gainesville, FL; B. Gila, K.P. Lee, A. Onstine, C.R. Abernathy, S.J. Pearton, Department of Materials Science and Engineering, University of Florida, Gainesville, FL; J.H. Shin, Samsung Electronics, Kyungki-Do, KOREA.

GaN metal oxide semiconductor (MOS) diodes were demonstrated utilizing MgO as gate oxide. A 4000 layer Å of MgO was grown at 100°C on the MOCVD grown n-GaN in a gas-source molecular beam epitaxy (GSMBE) system using electron beam deposition from a MgO source. MOS diodes were fabricated with wet-chemical etching the oxide to expose the underlying n-GaN for ohmic metal deposition. Electron deposited Ti/Al/Pt/Au and Pt/Au were used as ohmic and gate metallization. The diode reverse breakdown voltage was ~60V, while forward breakdown occurred at ~42V, giving a breakdown field of ~1 MV/cm. An interface trap density (Dit) of low-to-mid 10^{11} $eV^{-1}cm^{-2}$ was obtained with temperature conductance-voltage (G-V) measurement. The interface trap densities were determined as function of gate bias by changing the measured frequency at room temperature. Results of conductance measurements performed at elevated temperature (up to 300°C) and with ultraviolet illumination (photo-assisted C-V) will also be presented.

I11.31
STABILITY OF GaN MOS DIODES. K. Allums, B.P. Gila, Dept. of Materials Science and Eng., University of Florida, Gainesville, FL; B. Luo, R. Mehandru, Dept. of Chemical Eng., University of Florida, Gainesville, FL; R. Dwivedi, T.N. Fogarty, R. Wilkins, Center for Applied Radition Research, Prairie View A&M University, Prairie View, TX; F. Ren, Dept. of Chemical Eng., University of Florida, Gainesville, FL; C.R. Abernathy, and S.J. Pearton, Dept. of Materials Science and Eng., University of Florida, Gainesville, FL.

This paper will discuss the stability of GaN MOS diodes fabricated using the novel gate dielectrics Gd_2O_3 and Sc_2O_3. These dielectrics were deposited using molecular beam epitaxy onto MOCVD-grown GaN on sapphire. Both thermal stability and the effects of proton radiation on GaN MOS diodes were investigated. The stability of GaN Schottky diodes was also investigated for comparison. Electrical characterization, such as I-V and C-V, have been employed to monitor any change in the electrical characteristics of the diodes. Preliminary testing has shown that the GaN-based diodes are in fact affected by proton irradiation. Doses equivalent to 10 years in low earth orbit, ~5x10^9, produce a decrease in the reverse breakdown field in both Schottky and MOS diodes. However, even after irradiation the GaN MOS diodes show twice the reverse breakdown voltage of non-irradiated Schottky diodes. Further, while the Schottky diodes show reduced forward breakdown voltage, the MOS diodes show no change in forward breakdown. These results suggest that the oxide/GaN interface is stable and is not being damaged by the radiation, while the GaN surface in the Schottky diode is substantially degraded. The change in reverse breakdown is most likely due to generation of damage in the GaN resulting in the formation of shallow donors. Similarly, annealing of GaN/ Gd_2O_3 MOS diodes was found to produce no structural degradation in the oxide as measured by x-ray diffraction. The effect of annealing on damage recovery in the irradiated samples will also be discussed.

I11.32
EFFECTS OF *IN-SITU* AND *EX-SITU* SURFACE TREATMENT ON OHMIC AND SCHOTTKY CONTACTS TO ETCHED *n*-GaN. Rajwinder Singh, Ignacio Rodriguez, C.R. Eddy, Jr., and T.D. Moustakas, Boston University, Dept. of Electrical & Computer Engineering, Boston MA; H.M. Ng, Bell Labs, Lucent Technologies, Murray Hill, NJ.

The high strength of the bonds between nitrogen and the group-III elements is responsible for the attractiveness of III-nitride family of compound semiconductors for high frequency, high power and high temperature applications. However, the high bond strength necessitates energetic bombardment for effective etching of structures constituting many practical devices including light-emitting diodes, solar-blind ultraviolet detectors, vertical conduction GaN devices and GaN/AlGaN HFETs with recessed contact structures. A consequence of energetic bond breaking is the surface damage incurred by the III-nitride films, which is found to substantially degrade ohmic and barrier contacts (from 1.5×10^{-5} $\Omega\cdot cm^2$ to 1.0×10^{-4} $\Omega\cdot cm^2$ for film with n = 6.28×10^{18} cm^{-3}). Low contact resistance, good ohmicity and good quality of Schottky barrier contacts are highly desirable characteristics for better device performance. This paper reports the results of investigations aimed at studying the effects of post-etch *ex-situ* surface treatments as well as *in-situ* techniques involving modifications of plasma chemistry and rf bias energies during the etch. These investigations have been carried out in an inductively-coupled plasma etching reactor deploying a chlorine chemistry for etching. Results on the rapid recovery of contact quality by rapid thermal annealing at 700°C are also included, showing that most of the improvement in contact quality takes place in the first 30 seconds of annealing. Annealing this way, the specific contact resistance of GaN film with n = 6.28×10^{18} cm^{-3} was found to improve from 2×10^{-3} $\Omega\cdot cm^2$ to 1.5×10^{-5} $\Omega\cdot cm^2$.

I11.33
PRODUCTION of HIGH QUALITY AlGaN/GaN HFET STUCTURES ON SiC USING A MULTIWAFER MOCVD REACTOR. H.M. Wang, J.W. Yang, Q. Fareed, M. Asif Khan, University of South Carolina, Department of Electrical Engireering, Columbia, SC.

SiC with a thermal conductivity much higher than sapphire is an ideal choice for nitride high power devices. We report here the successful growth of high quality AlGaN/GaN HFETs on SiC and sapphire substrates using a multiwafer (6, 2 wafers per run) metalorganic chemical vapor deposition (MOCVD) system. The wafers were analyzed for their thickness, sheet carrier density and mobility values over the 2 face using an Accent RMP2000 and a rf-current probe system. These statistical data were used to optimize the growth process. The standard deviation of thickness and conductivity are respectively less than 2% and 8% across the six samples from a single run. The average value of mobility at room temperature was measured to be 1800 cm^2/V.s for sapphire and 2010 cm^2/V.s for SiC with sheet carrier density ns of 1×10^{13} cm^{-2}. The highest mobility in our mass-produced AlGaN/GaN HFETs was measured on I-SiC, namely, 14000cm^2/V.s at 77K. We attribute these high mobility values to an extremely sharp AlGaN/GaN interface. This was verified by the high resolution X-ray diffraction (HRXRD) where several orders of interference fringes at characteristic positions were observed. This

enabled us to simulate the cap layer thickness and Al composition values, which are found to be in a good agreement with our growth design. The atomic force microscopy (AFM) images clearly show growth steps with the height of one monolayer, indicating a layer-by-layer growth. The root mean square (RMS) roughness for a $5\times 5\mu$m area is only 2.6. In this paper the growth and characterization results will be discussed and correlated with the resulting device performance.

I11.34
CHARACTERISATION OF NITRIDE THIN FILMS BY ELECTRON BACKSCATTERED DIFFRACTION. C. Trager-Cowan, F. Sweeney, J. Hastie, S.K. Manson-Smith, D.A. Cowan and K.P. O'Donnell, Dept. of Physics and Applied Physics, University of Strathclyde, Glasgow, UNITED KINGDOM; D. Zubia and S.D. Hersee, University of New Mexico, Center for High Technology Materials, SE Albuquerque, NM; C.T. Foxon, I. Harrison and S.V. Novikov, University of Nottingham, Nottingham, UNITED KINGDOM.

The acquisition of electron backscattered diffraction (EBSD) patterns in the SEM is a very powerful method for the microstructural characterisation of crystalline materials. EBSD is at present predominantly used in metallurgy for the measurement of texture, i.e., the mapping of the orientation of individual grains in polycrystalline samples, and to identify different crystalline phases. However, Wilkinson [1] and Troost et al [2] applied EBSD to the measurement of strain in SiGe epilayers, while Baba-Kishi [3] has used EBSD to investigate crystallographic polarity of non-centrosymmetric structures. These results strongly suggest that EBSD may be a useful technique to apply to the characterisation of nitride thin films. In this paper we will describe some preliminary experiments that illustrate the power of EBSD for the microcharacterisation of nitride thin films. To date we have used EBSD to 1) reveal the relative orientation of a nitride thin film with respect to its substrate; 2) determine its tilt (a GaN thin film was found to be tilted by $13 \pm 1^{\circ}$) towards $[10\text{-}10]_{GaN}$), where the tilt is due to misorientation of the sapphire substrate (misoriented by 10° towards $(10\text{-}10)_{Sapphire}$); 3) detect improved surface quality in As-doped GaN films grown under high As_4 flux; and 4) observe more detail in EBSD patterns from cooled GaN thin films. We will also discuss results from our present studies. These include the investigation of nitride thin films of mixed phase, the measurement of strain and the measurement of polarity of both MOCVD and MBE grown nitride thin films. We will also describe results correlating the structural properties of nitride thin films revealed by EBSD with their luminescence properties revealed by photoluminescence and cathodoluminescence studies. [1] Angus J. Wilkinson, Ultramicroscopy 62 (1996) 237. [2] K.Z. Troost et al, Appl. Phys. Lett. 62 (1993) 1110. [3] K.Z. Baba-Kishi, J. Appl. Cryst. 24 (1991) 38.

I11.35
LOW-RESISTANCE ELECTRICAL CONTACTS TO P-TYPE GaN BY USING $In_xGa_{1-x}N$ CAP LAYERS. Thomas Gessmann, Yun-Li Li, John W. Graff, and E. Fred Schubert, Boston University, Electrical and Computer Engineering Department, Boston, MA; J.K. Sheu, Department of Electrical Engineering, National Cheng Kung University, Taiwan, PR CHINA.

Ohmic contacts with specific contact resistances less than 10^{-3} Ωcm^2 are of great importance for the stable and efficient operation of light-emitting devices fabricated from GaN compound semiconductor materials. Recently a new type of metal/p-type semiconductor contact has been demonstrated utilizing the internal electrical fields induced by polarization effects in strained Mg-doped $Al_xGa_{1-x}N$/GaN superlattices [1]; specific contact resistances as small as 9 x 10^{-4} Ωcm^2 have been achieved. Here we report on a modified approach employing a thin Mg-doped $In_xGa_{1-x}N$ ($x = 0.27$) cap layer on top of the p-type GaN barrier layer of a multi-quantum well LED structure. The acceptor concentration in the top InGaN and GaN layers as determined from capacitance-voltage is 3x10^{18} cm^{-3}. The specific resistance of a Ni/Au-contact metalization alloyed at 450°C was measured by the transmission line method for different current densities. The results are consistent with a current path independent of the applied voltage. At current densities typical for standard LED operation specific contact resistances of about 2 x 10^{-3} cm^2 were obtained. This value is compared to calculated results assuming a triangular potential barrier between the metal and the p-type cladding layer of the LED. Possibilities for further improvements by combining highly polarized cap layers and p-doped superlattices and by utilizing graded structures will be discussed. [1] Y.-L. Li, E.F. Schubert, J.W. Graff, A. Osinsky, W.F. Schaff, Appl. Phys. Lett. **76** (2000), 2728.

I11.36
FAST PROTON DAMAGE EFFECTS ON THE LUMINESCENCE PROPERTIES OF HIGH-QUALITY GaN. Henning Feick, Qing Yang, Rob Armitage, and Eicke Weber, Department of Materials Science and Engineering, University of California, Berkeley, CA.

Radiation damage studies of GaN provide insights into the fundamental properties of the material as well as the basic knowledge needed to predict degradation of GaN-based devices in space-based applications or other radiation environments. Due to the large concentration of grown-in defects in typical epitaxial GaN it has so far proven to be difficult to clearly identify the action of intrinsic radiation-induced defects. We study high-quality GaN layers grown by hydride-vapor phase epitaxy and homoepitaxial layers grown thereon by molecular beam epitaxy. Displacement damage-defects are introduced by fast protons with energy 25 MeV and 55 MeV. The protons easily penetrate all of the 160 um-thick layers i.e. no hydrogen-related defects are introduced. Proton fluences ranging between 3E12 and 3E14/cm^2 were used. With continuous-wave photoluminescence, we observe a radiation-induced increase in the yellow luminescence, indicating the introduction of Ga-vacancies. Time-resolved photoluminescence studies reveal a significant reduction of the carrier lifetime compared with the preirradiation value of several 100 ps. A recovery of the carrier lifetime is observed after extended room temperature storage. The luminescence spectra are investigated as a function of temperature in order to reveal the influence of the damage-induced nonradiative defect recombination on the luminescence efficiency. Results from isochronal annealing experiments and the influence of different doping concentrations of the homoepitaxial layers are discussed.

I11.37
FABRICATION OF AlGaN/GaN HETEROSTRUCTURE FIELD EFFECT TRANSISTOR WITH THERMALLY-STABLE SCHOTTKY CONTACT. C.M. Jeon, H.W. Jang, K.J. Choi, Jae-Hoon Lee[a], Jung-Hee Lee[a], Gil-Ho Kim[b], Kyu-Seok Lee[b], Bun Lee[b], J-L. Lee, Department of Materials Science and Engineering, Pohang University of Science and Engineering, Pohang, KOREA; [a]Department of Electronic and Electrical Engineering, Kyunpook National University, Teagu, KOREA; [b]Electronics and Telecommunications Reserch Institute, Daejeon, KOREA.

Reducing gate length and specific contact resistivity of Ohmic contacts is important in the realization of AlGaN/GaN heterostructure field effect transistor (HFET). As gate length is reduced, the space between source and drain becomes narrow, which makes it difficult to align and produce a fine gate pattern. If the gate metal was showed Schottky contact behavior up to annealing temperature for Ohmic contact, fine gate pattern would be obtained due to change of the sequence on the formation of source/drain and gate electrodes in process of HFET fabrication. However, no works has been conducted on the fabrication of AlGaN/GaN HFET using such process. The Schottky barrier height (SBH) of iridium Schottky contact on AlGaN/GaN HFET was increased about 0.4eV up to 400°C at which the specific contact resisvity of Ti/Al/Ni/Au Ohmic contact was 10^{-5} cm^2. Therefore source/drain electrodes could be formed after fine gate electrode and device performances improved after annealing using RTA at 400°C. In order to investigate the mechanism of SBH increase and leakage current decrease in iridium Schottky contact, secondary ion mass spectroscopy (SIMS) and XRD will be employed. The XRD analysis will show that iridium oxide was formed after annealing. The formation of iridium oxide will decrease unintentionally doping concentration at below the gate metal contact due to decrease of ON acting as donor in AlGaN. From SIMS analysis, gallium, nitrogen and oxygen distribution will be obtained from the compositional depth profile. From these analysises, the effect of iridium oxide formation in Schottky contact on AlGaN will be revealed and the HFET was fabricated using thermally-stable Shottky contact.

I11.38
TAILORABLE RECTIFICATION: A STUDY OF VERTICAL TRANSPORT IN AlGaN/GaN HETEROSTRUCTURES. Madhusudan Singh, Jasprit Singh, Department of Electrical Engineering and Computer Science, University of Michigan, Ann Arbor, MI; Umesh Mishra, Department of Electrical and Computer Engineering, University of California, Santa Barbara, CA.

In traditional metal-semiconductor junctions, it is possible to obtain Schottky like or ohmic behaviour by altering doping profiles. In this paper, we study the possibility of altering I-V characteristics of metal-AlGaN/GaN junctions by simply altering AlGaN thickness. The semiconductor structure is undoped and the device operation is based on controlling the polar charge effects present at the AlGaN/GaN interface. It has been demonstrated that sheet charge densities as high as 3×10^{13} cm^{-2} can be achieved at an undoped AlGaN/GaN interface by exploiting the piezoelectric effect and spontaneous polarization effects. We study the vertical transport in a metal-AlGaN/GaN system and exploit the polar charge effect to show that I-V characteristics can be altered to give: i) Schottky like behaviour; ii) tunnel junction behaviour with very small voltage turn on ($\sim$0.2 V); iii) Ohmic behaviour. The key to this tailorability lies in the choice of

AlGaN composition and thickness. In these calculations, we solve the Schrödinger and Poisson equations self-consistently and use the resulting band profile to calculate the current density through Monte Carlo integration. We have examined a number of structures but as an example, we provide results for the $Al_{0.28}Ga_{0.72}N$/GaN system. We find that if the AlGaN barrier thickness is larger than 50Å, the I-V response is Schottky like with a turn on voltage of ~1.1 V (for barrier thickness of 100 Å). However, if the AlGaN thickness is 25 Å, the structure acts as a tunnel diode with a turn on voltage of ~0.2 V. When the barrier thickness is much smaller (~10 Å), the response is once more Schottky like. Results will be presented for several combinations of AlGaN/GaN and AlGaN/InGaN/GaN structures.

I11.39
Abstract Withdrawn.

I11.40
CHEMICAL, ELECTRICAL, AND STRUCTURAL PROPERTIES OF Pd/Au CONTACTS ON CHEMICAL VAPOR CLEANED P-TYPE GaN SURFACES. P.J. Hartlieb, A. Roskowski, and R.F. Davis, North Carolina State University, Department of MS&E, Raleigh, NC; B.J. Rodriguez and R.J. Nemanich, Department of Physics, North Carolina State University, Raleigh, NC.

The chemical, electrical, and structural properties of Pd/Au contacts on chemical vapor cleaned p-type GaN (0001) surfaces have been studied using X-ray photoelectron spectroscopy (XPS), low energy electron diffraction (LEED), atomic force microscopy (AFM), scanning electron microscopy (SEM), and current-voltage (I-V) measurements. A high temperature NH_3 based chemical vapor clean (CVC) was used to obtain clean, ordered, stoichiometric p-type GaN surfaces with no detectable C, and an O constituent which was subsequently reduced from 15 atomic % on the conventional HCl treated surface to 2 ± 1 atomic % following the CVC process. Pd was observed to grow epitaxially on the CVC p-type GaN surface in a 2-D layer-by-layer fashion and subsequently formed an abrupt, unreacted metal-semiconductor interface. LEED images from the Au capping layer indicate epitaxial growth on the Pd contacting layer. Pd/Au contacts on both HCl and CVC treated surfaces exhibit identical surface roughness values (RMS) in the as-deposited state and following a 500°C anneal. Pd/Au contact structures on CVC treated surfaces demonstrate excellent high temperature structural stability as evidenced by no further change in the surface roughness (RMS) with successive annealing at 600, and 700°C. Identical contact structures on HCl treated surfaces exhibit poor high temperature structural stability as indicated by a significant increase in the surface roughness (RMS) following successive anneals at 600 and 700°C. There is a dramatic degradation in the morphology of both surfaces following an 800°C anneal as evidenced by the formation of large voids in the contact metallization and the subsequent exposure of the underlying p-type GaN. The lowest resistance contact structures with uniform metal coverage were obtained for Pd/Au contacts on a CVC treated surface annealed at 700°C.

I11.41
FABRICATION AND INVESTIGATION OF THE METAL-FERROELECTRIC-SEMICONDUCTOR STRUCTURE WITH THE PZT FILM ON AN AlGaN/GaN HETEROSTRUCTURE. B. Shen, W.P. Li, X.S. Wang, F. Yan, R. Zhang, Z.X. Bi, Y.G. Zhou, Z.W. Zheng, Y. Shi, Z.G. Liu, Y.D. Zheng, National Laboratory of Solid State Microstructures and Department of Physics, Nanjing University, Nanjing, CHINA; T. Someya, Y. Arakawa, Research Center for Advanced Science and Technology and Institute of Industrial Science, University of Tokyo, Tokyo, JAPAN.

AlGaN/GaN heterostructure field effect transistors (HFETs) are being developed rapidly. Recently, AlGaN/GaN HFET with a metal-insulator-semiconductor (MIS) gate structure has attracted increased attention. On the other hand, much effort has been made on integrating ferroelectrics into semiconductor technologies. Si is usually employed as a semiconductor channel in the metal-ferroelectric-semiconductor (MFS) FET. However, the ferroelectric/silicon interface interdiffusion is quite difficult to control during the high-temperature deposition of the ferrelectric film. GaN-based materials are stable at high temperatures. Because of its numerous advantages, an AlGaN/GaN heterostructure is possible as a practical semiconductor channel for MFS-FET. In this study, a MFS structure with a $Pb(Zr_{0.53}Ti_{0.47})O_3$ (PZT) film on a modulation-doped $Al_{0.22}Ga_{0.78}N$/GaN (AlGaN/GaN) heterostructure was developed. The AlGaN/GaN heterostructure was grown by metal-organic chemical vapor deposition on a sapphire substrate. The PZT film was deposited on the AlGaN layer by means of pulsed laser deposition. According to the high-frequency capacitance-voltage (C-V) measurement, the density of the two-dimensional electron gas (2DEG) at the AlGaN/GaN heterointerface in the MFS structure depends strongly on the ferroelectric polarization. Meanwhile, a C-V hysteresis window of 0.2 V with anti-clockwise direction is observed, which is the ferroelectric memory window caused by the polarization difference of the PZT film between the opposite sweeping directions. Due to its buried-channel property, the AlGaN/GaN MFS structure shows the memory window completely in the range of negative bias, indicating that the AlGaN/GaN MFS structure can produce the C-V window without the reversal of the ferroelectric polarization. This advantage may weaken the negative effect brought by the fatigue property of the ferroelectric film on the memory performance.

I11.42
EXTRACTION OF POLARIZATION-INDUCED CHARGE DENSITY IN MODULATION-DOPED AlGaN/GaN HETEROSTRUCTURES THROUGH SCHOTTKY CAPACITANCE-VOLTAGE SIMULATION. Y.G. Zhou, B. Shen, H.Q. Yu, R. Zhang, J. Liu, H.M. Zhou, Z.W. Zheng, Y. Shi, Y.D. Zheng, National Laboratory of Solid State Microstructures and Department of Physics, Nanjing University, Nanjing, CHINA; T. Someya, Y. Arakawa, Research Center for Advanced Science and Technology and Institute of Industrial Science, University of Tokyo, Tokyo, JAPAN.

AlGaN/GaN heterostructure field-effect transistors (HFETs) for high power, high temperature, and microwave applications are being rapidly developed. Due to the lattice mismatch between AlGaN and GaN, as well as the high piezoelectric paramenter of III-nitrides, the polarization-induced electric field near the heterointerface leads to a significant increase of the sheet concentration and the narrower confinement of the two-dimensional electron gas in AlGaN/GaN heterostructures in comparison with that in AlGaAs/GaAs ones. Quantitative characterization of the polarization field is necessary for a better understanding of the polarization and the strain relaxation in AlGaN/GaN heterostructures. In this study, a new method based on the Schottky capacitance-voltage (C-V) simulation is developed to extract the polarization-induced charge density in modulation-doped AlGaN/GaN heterostructures. C-V measurements are performed on the Schottky contacts on modulation-doped AlGaN/GaN heterostructures, where the Al fraction in AlGaN is 22%. The C-V characteristics are numerically simulated using 3D-Fermi model. There are two characteristic slopes in the experimental and simulated C-V curves. As seen through the simulation, the influence of changing the polarization-induced charge density, the doping level of the AlGaN barrier and the Schottky barrier height on the positions of the two slopes in the C-V curves are much different. Therefore, the polarization-induced charge density can be extracted accurately when the positions of the two slopes of the simulated C-V curve agrees well with those of the experimental one. From the simulation, the polarization-induced sheet charge density is extracted to be 6.78 x 10^{12} cm^{-2} in the samples with the AlGaN thickness of 30 nm or 45 nm. The charge density reduces to 1.30 x 10^{12} cm^{-2} in the sample with the AlGaN thickness of 75 nm. The reduction of the polarization-induced charges at the heterointerface is due to the partial relaxation of the AlGaN layer on GaN.

I11.43
TEM ASSESSMENT OF GaN/AlGaN/TiAlTiAu AND GaN/AlGaN/TiAlPdAu OHMIC CONTACTS. M.W. Fay, G. Moldovan, P.D. Brown, School of Mechanical, Materials, Manufacturing Engineering and Management, University of Nottingham, UNITED KINGDOM; I Harrison, School of Electrical and Electronic Engineering, University of Nottingham, UNITED KINGDOM; J.C. Birbeck, B.T. Hughes, M.J. Uren, T. Martin, DERA, Malvern, UNITED KINGDOM.

Ti/Al/Ti/Au contacts to AlGaN/GaN, rapid thermal annealed at temperatures ranging from 650°C to 950°C, have been investigated using HRTEM, EFTEM imaging and EDX analysis. Ohmic behaviour was seen for contacts annealed at 750°C or higher. The effect of annealing temperature on the structural evolution of the contact is explained in terms of different extents of interfacial reactions. In particular, the formation of a TiN layer at high temperatures is described. At anneals of 950°C a structure of Ti-rich interfacial grains and TiN inclusions into the AlGaN is formed. An Al-Au diffusion front ahead of the TiN inclusions was detected. The mechanism of inclusion formation and the effect on the contact electrical performance is considered. Comparison is made to the structure of TiAlPdAu contacts to AlGaN/GaN.

I11.44
EFFECTS OF THE SCHOTTKY ELECTRODE STRUCTURE IN GaN BASED UV-VUV (50-360 NM) PHOTODETECTOR. Atsushi Motogaito, Keiichi Ohta, Kazumasa Hiramatsu, Mie University, Department of Electrical and Electronic Engineering, Tsu, Mie, JAPAN; Youichiro Ohuchi, Kazuyuki Tadatomo, Mitsubishi Cable Industries, LTD., Photonics Research Laboratory, Itami, Hyogo, JAPAN; Yutaka Hamamura, Nikon Corporation, Precision Equipment Company, Sagamihara, Kanagawa, JAPAN; Kazutoshi Fukui, Research Center for Development of Far-Infrared Region, Fukui Univ.,

Fukui, Fukui, JAPAN.

Ultraviolet (UV) detectors are one of the most attractive devices in the group III-nitride semiconductors. Several groups have reported on GaN or AlGaN based UV detectors. They have responsivity from 250 to 360 nm (3.4 - 5.0 eV) and clear cut-off characteristics at a cut-off wavelength (360 nm). We had already reported on the responsivity spectra of Schottky type UV detectors with a comb-shaped electrode in the vacuum ultraviolet (VUV) region for the first time, we succeeded in operating the detectors without any photoemission current from Au and GaN less than 9.5 eV (>130 nm), however photoemission of GaN causes at higher than 9.5 eV (<130 nm). We realized the higher responsivity spectra of Schottky type UV detectors with transparent electrode between VUV and visible light region (50-563 nm, 2-25 eV) by suppressing the photoemission of GaN. Synchrotron radiation at UVSOR was used to measure the spectra. The responsivity spectra of the detectors at 0 V bias were obtained in the wide range between 2 eV (563 nm) and 25 eV (50 nm). We were able to cancel the photoemission current from Au electrode by improving the measuring circuit, and thus we succeeded in operating the detectors without any photoemission current from Au and GaN. The responsivity of the detectors is about 0.15 A/W at 3.5 eV. Compared to the results of comb-shaped structure, the responsivity moved a figure to the left and the operating range without any photoemission of transparent structure is wider than that of comb-shaped structure. These results show that these Schottky type detectors with the transparent electrode are effective to detect VUV-UV light (50 - 360 nm, 3.4 - 25 eV) without any photoemission.

I11.45
ANALYSIS OF THE THERMAL DISTRIBUTION DURING CW-OPERATION OF MOUNTED InGaN LASER DIODES.
Volker Kümmler, Georg Brüderl, Stefan Bader, Andreas Weimar, Alfred Lell, Volker Härle, Osram Opto Semiconductors GmbH & Co. OHG, Regensburg, GERMANY.

OSRAM OS is developing InGaN/GaN-MQW-laser diodes at wavelengths around $\lambda = 400 - 420\,\mathrm{nm}$ which could be used in high density data storage and laser printing. N-Conducting SiC is used as substrate, which makes edge emitting lasers with a vertical current path and cleaved and coated mirror facettes possible. These devices show threshold current densities of $j_{\mathrm{th}} = 6.3\,\mathrm{kA/cm^2}$ with Reflectiveness R=70/90% and voltages of $U_{\mathrm{th}} = 12,5\,\mathrm{V}$. One major obstacle in the commercialization of blue laser diodes are the low lifetimes of the devices. The lifetime is highly dependent on the temperature profile during operation. Therefore it is crucial to lower the temperature in the device by mounting the diodes either p-side up or down on heat sinks. Most heat is generated at the p-contact and the active layer, so that p-side down mounting should be favorable. P-side down mounted diodes on a heat sink have shown 2 minutes of CW-lasing (T = 25°C) at 1 mW optical power. The device shows a thermal resistance of $R_{\mathrm{th}} = 25\mathrm{K}/W$ which is significantly lower than resistances for lasers grown on sapphire. We have investigated the lasing behavior for similar diodes on different heat sinks and with p-side up or down mounting. These experimental measurements are compared to a thermal conduction model including different mounts, mounting ways and resonators geometries. Measured and calculated thermal resistance is compared. It is shown that a large part of the heat is transferred through the SiC-substrate due to its excellent thermal conductivity.

I11.46
DIRECT COMPARISON OF AlGaN/GaN HEMTs GROWN ON SAPPHIRE AND AlN/SiC SUBSTRATES.
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The material quality and device performance of AlGaN/GaN high electron mobility transistors (HEMTs) grown on AlN/SiC and sapphire substrates were studied. The AlN/SiC substrate consisted of 200 nm AlN grown by hydride vapor phase epitaxy (HVPE) on the (0001)Si face of a 6H-SiC substrate. The AlGaN/GaN epitaxial layers were grown by metal organic chemical vapor deposition (MOCVD) at 1050°C. Cross-sectional transmission electron microscopy (XTEM) showed that the defect density was orders less for the HEMTs grown on AlN/SiC. Surface morphology was investigated by atomic force microscopy (AFM). HEMTs were fabricated by conventional processing steps, including Cl-based ICP mesa etch, Ti/Al/Pt/Au metallization annealed at 850°C, and Ni/Au gate metallization. Mushroom gates with lengths ranging from 0.1 to 1.2 μm and widths from 50 to 650 μm were studied. DC, RF, and high temperature device characteristics will be reported.

I11.47
ELECTRICAL CHARACTERIZATION OF SCANDIUM OXIDE/GaN AS MOS STRUCTURES.
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GaN metal oxide semiconductor (MOS) diodes were demonstrated utilizing Sc_3O_2 as gate oxide. A 1200 Å layer of Sc_3O_2 was grown at 100°C on the MOCVD grown n-GaN in a gas-source molecular beam epitaxy (GSMBE) system using elemental Sc and an electron cyclotron resonance (ECR) oxygen plasma. SEM micrographs show a smooth surface without evidence of pinholes. MOS diodes were fabricated with dry etching for the oxide in an inductively coupled plasma (ICP) system to expose the underlying GaN for ohmic metal deposition. Electron beam deposited Ti/Al/Pt/Au and Pt/Au were used for ohmic and gate metallization. The diode reverse breakdown voltage was ~20V, while forward breakdown occurred at ~7V, giving a breakdown field of ~0.6 MV/cm. Capacitance-voltage (C-V) data were recorded at different frequencies up to 1 MHz. Clear charge modulation from accumulation to depletion was observed. Using Terman's method at room temperature, a minimum interface state density in the mid-10^{11} $\mathrm{eV^{-1}}$-$\mathrm{cm^{-2}}$ was obtained, while AC conductance measurements gave a value in the low-10^{12} $\mathrm{eV^{-1}}$-$\mathrm{cm^{-2}}$. Results of C-V measurements performed at high temperature (up to 300°C) and with ultraviolet illumination (photo-assisted C-V) will also be presented.

I11.48
COMPARISON OF OPTICAL PROPERTIES OF 340nm-BAND BRIGHT UV-LEDs BETWEEN InAlGaN AND AlGaN ACTIVE REGION.
Hideki Hirayama[a], Atsuhiro Kinoshita[a,b], Makoto Ainoya[a,b], Takayoshi Yamabi[a,b], Takuya Yamanaka[a,b], Akira Hirata[b], and Yoshinobu Aoyagi[a]; [a]RIKEN (The Institute of Physical and Chemical Research), Saitama, JAPAN; [b]Waseda Univ., Tokyo, JAPAN.

We demonstrated high intensity ultraviolet (UV) (345nm) emission from InAlGaN quaternary light emitting diode (LED) operating at room temperature. The emission intensity of InAlGaN-UV-LED was much stronger than that of AlGaN or GaN-UV-LEDs. InAlGaN quaternary is very attractive for the realization of 300 nm-band UV laser diodes (LDs) and bright LEDs, because both room temperature (R.T.) intense UV emission and hole conductivity can be obtained for wide bandgap InAlGaN, due to In segregation effects. We have already achieved 300-340nm intense photoluminescence (PL) from InAlGaN/InAlGaN quantum wells (QWs) at R.T. and also hole conductivity for InAlGaN with the bandgap more than 4 eV. In this report, we compare the electroluminescence properties of UV-LEDs between InAlGaN and AlGaN active regions. LED structures were grown on 6H-SiC substrate by metal-organic vapor-phase-epitaxy (MOVPE). The structure is consisting of Si-doped $Al_{0.18}Ga_{0.82}N$ buffer layer, i-$In_{0.05}Al_{0.34}Ga_{0.61}N$ quaternary emitting layer (80nm), Mg-doped $Al_{0.18}Ga_{0.82}N$ layer and Mg-doped GaN capping layer. We obtained single peak bright emission of 345 nm from fabricated InAlGaN-LEDs with R.T. CW operation. The emission spectrum and the intensity of the UV-LEDs were compared between InAlGaN, AlGaN and GaN active regions. The UV intensity from InAlGaN-LED was more than one order of magnitude larger compared with AlGaN or GaN-LEDs. There was no emission from deep levels such as acceptor levels or yellow bands for InAlGaN-UV-LEDs. The photoluminescence intensity from InAlGaN/InAlGaN QW was comparable as that of InGaN QW at R.T.. From these results, InAlGaN quaternary is much expected for the realization of 300-340 nm UV-LDs.

I11.49
OPTICAL ABSORPTION OF GaN UNDER UNIAXIAL STRAIN COMPRESSION.
H.Y. Peng, M.D. McCluskey, Y.M. Gupta, Institute for Shock Physics and Department of Physics, Washington State University, Pullman, WA.

The band gap shift of undoped and Mg-doped GaN epilayer on (0001)-oriented sapphire has been studied in detail as a function of uniaxial strain compression along the c-axis using time-resolved, optical absorption measurements in shock wave experiments. For longitudinal stresses ranging from 4 to 14 GPa, the band gap shift is approximately 0.02 eV/GPa for both undoped and Mg-doped GaN. However, the absolute band gap shift of Mg-doped GaN is larger than that of undoped GaN. Ab initio calculations reveal that this experimental slope lies between the theoretical value of 0.013 eV/GPa for uniaxial compression and 0.038 eV/GPa for isotropic compression. This fact suggests that shocked GaN may undergo a deformation

containing both uniaxial and isotropic components. Meanwhile, a slow band gap shift is also observed following the immediate band gap increase upon impact. Due to the strong piezoelectric effect in III-nitride compounds, a large electric field is expected to be present along the c-axis during shock loading, resulting in the Franz-Keldysh effect. Using very thin (100 nm) undoped GaN, we are able to observe the whole absorption spectrum and make comparisons with theoretical predictions quantitatively. Broadening and oscillation of the absorbance spectrum are both observed for photon energies below and above the band gap, respectively. * This work was supported by the US Department of Energy (Grant DEFG0397SF21388).

I11.50
PHOTOLUMINESCENCE STUDIES OF ERBIUM AND EUROPIUM DOPED GALLIUM NITRIDE PREPARED BY SOLID SOURCE MOLECULAR BEAM EPITAXY (SSMBE). U. Hommerich, Ei Ei Nyein, J.T. Seo, A. Braud, Hampton Univ, Dept. of Physics, Hampton, VA; J. Heikenfeld, D.S. Lee, A.J. Steckl, Univ. of Cincinnati, Nanoelectronics Lab, Cincinnati, OH; J.M. Zavada, U.S. ARL-European Research Office, London, UNITED KINGDOM.

We are currently engaged in a spectroscopic evaluation of Er doped GaN and Eu doped GaN for possible applications as Electro-luminescent Phosphors. The investigated samples were grown by solid-source molecular beam epitaxy on Si (111) substrates. Under above-gap pumping, characteristic green (~537, 558 nmnm) and red emission lines (~622nm) were observed from Er3+ and Eu3+, respectively. Integrated PL intensity studies revealed that the green emission from GaN: Er was quenched by ~40% as the temperature increased from 15 to 300 K. The red emission from GaN: Eu decreased more rapidly for the same temperature range and was quenched by ~90% at room temperature. On the contrary, temperature dependent lifetime measurements suggest that non-radiative decay processes only weakly affect the intra-4f rare earth luminescence in both systems. The observed PL quenching is therefore attributed to a temperature dependence of the carrier-mediated energy transfer process from the semiconductor host to the rare earth center. A more detailed discussion of the luminescence efficiency, excitation efficiency, and rare earth concentration dependence will be presented at the conference.

SESSION I12: ELECTRONIC DEVICES
Chair: Umesh K. Mishra
Friday Morning, November 30, 2001
Room 302 (Hynes)

8:30 AM *I12.1
NOVEL SENSOR APPLICATIONS OF III-NITRIDES. Oliver Ambacher, Martin Eickhoff, Gerhard Müller, Ralf Neuberger, Jan Schalwig, Georg Steinhoff, Martin Stutzmann, Walter Schottky Institute, Technical University Munich, Garching, GERMANY.

In addition to the by now well established applications of III-nitrides in optoelectronics and for high temperature/high frequency transistors, GaN and AlGaN/GaN-heterostructures also have a great potential for a large variety of sensor devices. Solar blind UV-sensors are the best known example of III-nitride sensors so far. However, recent work has shown that nitrides can also be used for a large number of other sensor functions. Thus,simple Pt/GaN Schottky diodes are significantly influenced by the presence of a large number of gases relevant for the polution control of combustion engines. Similarly, AlGaN/GaN-heterojunctions with their characteristic polarization-induced two-dimensional electron gas turn out to be very sensitive to external pressure, wetting by liquids, or exposure to free ions. This talk will present the main experimental observations obtained so far for sensor applications of III-nitrides and first attempts to understand the physics behind these phenomena. The possibility to integrate optoelectronics, electronics, sensor functions, and even micromechanics in the same material system opens up exciting possibilities for smart sensors.

9:00 AM I12.2
HIGH COMMON - EMITTER CURRENT GAINS OBTAINED BY PNP GaN BIPOLAR JUNCTION TRANSISTORS. Kazuhide Kumakura, Toshiki Makimoto, Naoki Kobayashi, NTT Basic Research Laboratories, Kanagawa, JAPAN.

GaN-based semiconductors have attracted much attention for realizing electronic devices that can operate at high temperature and/or high power as well as at high frequencies. Bipolar junction transistors (BJTs) potentially have more uniform threshold voltages, higher linearity and higher current densities than field effect transistors as well as low phase noise. There have been several reports on npn GaN BJTs and AlGaN/GaN or InGaN/GaN heterojunction bipolar transistors (HBTs). For the pnp configuration, the base resistance can be reduced because electron concentrations are high enough for n-type GaN. However, for pnp GaN-based BJTs and HBTs only common-base characteristics have been shown, since common-emitter characteristics were degraded due to leakage in the collector-base junction. In this conference, we will report practically important common - emitter current - voltage (I-V) characteristics of pnp GaN BJTs. The device structures were grown by low-pressure metalorganic vapor phase epitaxy on c-face sapphire substrate. First, a GaN buffer layer was deposited at 500°C. Next, a 0.6-μm-thick undoped GaN layer, a 1-μm-thick Mg-doped GaN subcollector and a 1.2-μm-thick undoped GaN collector were grown at 1000°C. Then, a 0.12-μm-thick Si-doped GaN base and a 0.24-μm-thick Mg-doped GaN emitter were grown. The hole concentration of the emitter and subcollector was 1×10^{18} cm^{-3} and that of the collector was estimated to be lower than mid-10^{17} cm^{-3}. The electron concentration of the base was mid-10^{17} cm^{-3}. The emitter size was 90×150 μm^2. Pd/Au metals were used for emitter and subcollector contacts, and Al/Au for the base contact. Current saturation features were observed in the common - emitter I-V characteristics at room temperature. From these common-emitter I-V characteristics and gummel plots, the maximum current gain of 50 was obtained for collector current ranging from 10^{-5} to 10^{-4} A.

9:15 AM I12.3
Si_3N_4/AlGaN/GaN- METAL-INSULATOR-SEMICONDUCTOR HETEROSTRUCTURE FIELD EFFECT TRANSISTORS. G. Simin, X. Hu, A. Koudymov, A. Tarakji, J. Yang, M. Asif Khan, Univ. of South Carolina, Dept. of Electrical Engineering, Columbia, SC; M.S. Shur and R. Gaska, Sensor Electronic Technology, Inc., Latham, NY.

Using AlGaN/GaN heterostructure field-effect transistors (HFETs) impressive powers in the range of 5-10 W/mm have been demonstrated at operation frequencies ranging from 2-10 GHz. Two key problems however still persist. First, the gate leakage current for the HFET devices is typically 0.1 - 1 A/mm^2 at room temperature and it rapidly increases with temperature thereby increasing low and high frequency noise level and the thermal stress related device degradation. Secondly, the HFETs exhibit current collapse with a high rf-input drive on the gate [1-3], which significantly suppresses the RF-power below the values expected from DC-transfer curves. In past Si_3N_4 passivation has been shown to reduce current collapse. We have also reported on a MOSHFET with insulating oxide layer under the gate. Now combining these two approaches we report on a novel Si_3N_4 based Metal-Insulator-Semiconductor HFET (MISHFET) with simultaneous current collapse and gate leakage current reduction. The MISHFETs can operate at positive gate biases as high as 10 V that nearly doubles the channel current as compared to conventional AlGaN/GaN HFETs of a similar design grown on the same wafer. The cut-off frequency of MISHFETs is about 20% higher compared to HFETs. The gate-leakage current was measured to be 4 orders lower than an identical geometry HFET. This reduction maintained itself even at temperatures as high as 700°C. By measuring rf-powers and the corresponding operating DC currents we demonstrate collapse-free high power RF- performance from MISHFETs.

1. C. Nguyen, N.X. Nguyen and D.E. Grider, IEEE El. Device Lett, Vol. 35, No. 16 (1999)
2. E. Kohn, I. Daumiller, P. Schmid, N.X. Nguyen and C.N. Nguyen, El. Lett, 35, 1022-1024 (1999)
3. S. Binari, K. Ikossi, J. Roussos, W. Kruppa, D. Park, H. Dietrich, D. Koleske, A. Wickenden, and R. Henry. IEEE Trans. on ED, V. 48, 465 - 471 (2001)

9:30 AM I12.4
SELF-HEATING EFFECTS IN HIGH-POWER AlGaN/GaN HFETs. M. Kuball, J.M. Hayes, University of Bristol, H.H. Wills Physics Laboratory, Bristol, UNITED KINGDOM; T. Martin, M.J. Uren, J.C.H. Birbeck, R.S. Balmer, B.T. Hughes, Defence Evaluation and Research Agency (DERA), Great Malvern, UNITED KINGDOM.

Self-heating effects limit the performance of high-power AlGaN/GaN heterostructure field effect transistors (HFETs). Good thermal management using substrates with high thermal conductivity such as SiC or using flip-chip bonding has therefore proven essential to achieve power densities as high as 9W/mm. Knowledge of the temperature in the active area of AlGaN/GaN HFETs is essential for optimizing device design, performance and reliability, however, direct measurement of this temperature is not readily achieved. Infrared techniques often employed to measure the temperature of an active device require extensive calibration and have limited spatial resolution when compared with the micron-size source-drain opening in high-power AlGaN/GaN HFETs. We report on the in-situ measurement of temperature, i.e., self-heating effects, in high-power AlGaN/GaN HFETs grown on sapphire and on SiC substrates. Optical micro-spectroscopy was used to measure temperature with 1μm spatial resolution. Temperature rises as large as 170°C were measured in HFETs grown on sapphire substrates at a power dissipation of only 0.7W, whereas for HFETs grown on SiC substrates temperature rises of 75°C were measured at a power dissipation as large as 2W. The power-dependence of the device temperature as well as the spatial temperature distribution in the source-drain opening of

AlGaN/GaN HFETs was investigated and related to the device performance. A comparison with theoretical models of temperature distribution in high-power HFETs is presented. Acknowledgement: The DERA contribution to this work was undertaken as part of TG7 and TG9 of the UK MoD Corporate Research Programme.

9:45 AM I12.5
NOISE PROPERTIES OF GaN/AlGaN HFETS AT TEMPERATURES FROM 8K TO 300K. Sergey L. Rumyantsev, Yanqing Deng, Wojciech Knap, Michael S. Shur, Elena Borovitskaya, Alexandr Dmitriev, Nezih Pala, Rensselaer Polytechnic Institute, Dept of Electrical Computer and Systems Engineering, Troy, NY; Remis Gaska, Xuhong Hu, Sensor Electronics Technology Inc, Latham, NY; Asif M. Khan, Grigory S. Simin, Jinwei Yang, University of South Carolina, Dept of Electrical and Computer Engineering Columbia, SC; Michael E. Levinshtein, Ioffe Institute Sol St Electronics Division, St. Petersburg, RUSSIA.

We present experimental and theoretical results which link 1/f noise in GaN-based HFETs to the tunneling from the 2D gas to a shallow donor level with the activation energy ~20 meV. The 1/f noise spectrum is caused by the stochastic tunneling of electrons to shallow donor located at different distances from 2D electron gas at the heterointrface. The model predicts that the temperature dependence of the 1/f noise should have a maximum when the electron Fermi level crosses the shallow donor level. We measured the temperature dependence of noise spectra in GaN/AlGaN HFETs at temperatures from 8K to 300K and observed such maximum. The structures were grown by low pressure MOCVD on SiC substrates. A 150 nm AlN layer was followed by the deposition of 1000 nm GaN layer. Finally the structure was capped with a 40 nm AlGaN barrier layer. At T=300K, the 1/f noise was characterized by the Hooge parameter α=(1-3) $\times 10^{-4}$. The temperature dependence of the 1/f noise exhibited a very broad maximum at temperatures T=100 K. The temperature of that maximum does not depend on frequency. These results are in a qualitative agreement with the model. Our model predicts that the level of 1/f noise should be considerably smaller in undoped HFETs. This prediction is in a qualitative agreement with the results of Balandin et al (Appl. Phys. Lett., v.75, p.2064, 1999) At T=8-15 K, the contribution of the generation recombination (g-r) noise from the local level has been found. The characteristic time of the g-r process was found to be only weakly dependent on temperature.

10:30 AM I12.6
AlGaN/GaN HEMT PERFORMANCE LIMITS. Lester Eastman, Electrical and Computer Engineering, Cornell University, Ithaca, NY.

Nitride HEMT's on SiC substrates have set new state-of-the-art in normalized CW power at 10 GHz, reaching 11 W/mm for small periphery devices. For 1.5 mm periphery devices, 10 W CW has been obtained with 40% power-added efficiency at the same frequency. Power-added efficiency of the former devices at low bias is in the 60-70% range, while it is in the range of 50-60% for the latter devices. The drop in efficiency at higher drain bias is attributed to the rapidly rising channel sheet resistance with temperature, and can be controlled by better heat sinking and bias conditions. Frequency response to date has been limited by the average electron transit velocity of 1.3 x 10^7cm/s. Means of raising this velocity, and the frequency response, by 50% will be presented, along with initial experimental results. A nitride HEMT monolithic wave amplifier capable of 15-20 V pulse amplitude at 40 GB/s for driving lithium niobate light modulators, will also be presented. Research has been supported by ONR MURI contract N00014-96-1-1223 monitored by Dr. John Zolper, and by GE/CRD, Northrop Grumman, Raytheon, Teledyne, Triquint, and Welch-Allyn.

10:45 AM I12.7
A HIGH-POWER AlGaN/GaN HETERO FIELD-EFFECT TRANSISTOR. Seikoh Yoshida and Hirotatsu Ishii, Yokohama R&D Laboratories, The Furukawa Electric Co., Ltd, Yokohama, JAPAN.

GaN-based materials are very promising for electric devices which can be used under high-power, high-frequency, and high-temperature conditions. Especially, it is expected that the on-state resistance of a GaN field-effect transistor (FET) is lower than that of Si or GaAs devices. However, there is no experimental report concerning the on-state resistance of a GaN-based FET. In this paper, it is reported for the first time that an AlGaN/GaN hetero FET (HFET) was operated above 15 A, and that the on-state resistance of the HFET is lower than that of a Si-based FET. GaN and related materials were grown by gas-source molecular beam epitaxy (GSMBE). Sapphire substrates were used for GaN growth. A undoped GaN/$Al_{0.2}Ga_{0.8}N$ heterostructure was grown on the substrate. After that, a large-size $Al_{0.2}Ga_{0.8}N$/GaN HFET was fabricated. The gate width was 20 cm and the gate length was 2 μm. The source and drain also had a multi-finger structure. The electrode materials of the source and the drain were Al/Ti/Au and the Schottky electrodes were Pt/Au. The distance between the source and drain was 6 μm. The FET structure was fabricated using a dry-etching technique. Multi-electrode structures were also fabricated using SiO_2 for isolating the source, drain, and gate electrodes, respectively. The HFET was operated at a current of over 15 A. The on-state resistance of the HFET was about 2 mΩcm^2. The transconductance (g_m) of this HFET was about 120 mS/mm. It was also confirmed that the breakdown voltage was over 600 V and the breakdown field of an undoped high resistive GaN buffer was over 1.3 MV/cm. Therefore, a high power AlGaN/GaN HFET was demonstrated.

11:00 AM I12.8
BACK-DOPING DESIGN IN AlGaN/GaN HETEROSTRUCTURE FIELD-EFFECT TRANSISTORS FOR HIGH-POWER APPLICATIONS. Narihiko Maeda, Kotaro Tsubaki, Tadashi Saitoh, Naoki Kobayashi, NTT Basic Research Laboratories, NTT Corporation, Kanagawa, JAPAN.

The modulation doping (MD) design is commonly used in the AlGaN/GaN heterostructure field-effect transistors (HFETs). However, as the thickness of the AlGaN layer is reduced for higher device performance, the possible carrier supply from the barrier layer is decreased and comes to be less than the inherent large capacity for the two-dimensional electron gas (2DEG) density. To overcome this situation, we propose the back-doping (BD) design where high potentiality of the HFETs for high-power applications can be fully exploited. We have grown AlGaN/GaN HFETs with both MD and BD designs on SiC substrate by metalorganic vapor-phase epitaxy (MOVPE) at 300 Torr. In the MD $Al_{0.3}Ga_{0.7}N$/GaN HFETs, the AlGaN layer was doped with Si ((2-4)x10^{19} cm^{-3}) except for the spacer (30 Å) and Schottky contact (40 Å) regions. As the BD $Al_{0.3}Ga_{0.7}N$/GaN HFETs, the MD $Al_{0.3}Ga_{0.7}N$/GaN heterostructure was grown on the $Al_XGa_{1-X}N$ underlying layer (X=0.04-0.08) where a part of the region (100 Å) adjacent to the GaN channel was doped with Si. No abrupt discontinuity of the Al composition was included in all the underlying layers to eliminate the extra 2DEG other than the channel electrons. In MD HFETs, when the thickness of the $Al_{0.3}Ga_{0.7}N$ barrier layer was reduced to as thin as 120 Å, the maximum 2DEG density was decreased to 1.4x10^{13} cm^{-2}. With BD HFETs, however, the 2DEG density can be increased to well beyond 2x10^{13} cm^{-2} for the same thickness of the $Al_{0.3}Ga_{0.7}N$ layer. Corresponding room temperature 2DEG mobility (900 cm^2/Vs) was very high considering the high 2DEG density. In BD HFETs, negative polarization charges at the backside GaN/AlGaN heterointerface should raise the relevant potential profiles and helps to effectively supply electrons to the channel. The back-doping design is thus promising for high-power applications and even indispensable to fully exploit high potentiality of the AlGaN/GaN HFETs.

11:15 AM I12.9
HIGH QUANTUM EFFICIENCY OF AlGaN/GaN SOLAR-BLIND PHOTODETECTORS GROWN BY METALORGANIC CHEMICAL VAPOR DEPOSITION M.M. Wong[a], U. Chowdhury[a], C.J. Collins[a], B. Yang, J.C. Denyszyn[a], K.S. Kim[a], J.C. Campbell[a] and R.D. Dupuis[a], [a]The University of Texas at Austin, Microelectronics Research Center, Austin, TX.

Photodetectors operating in the wavelength range between 250 and 300 nm, referred to as the solar-blind regime, can be used for applications such as missile detection and tracking and for biological agent and chemical detection. We report the growth, fabrication and characterization of high-quality AlGaN/GaN solar-blind PIN and MSM photodetectors by low-pressure metalorganic chemical vapor deposition (MOCVD) with trimethylgallium (TMGa), trimethylaluminum (TMAl), bis (cyclopentadienyl) magnesium (Cp_2Mg), silane (SiH_4), and ammonia (NH_3) precursors. The epitaxial films were studied using X-ray diffraction, secondary ion mass spectroscopy, atomic force microscopy, and cathodoluminescence at both room temperature and 4K. We studied the correlation of the symmetric and asymmetric X-ray diffraction linewidths, surface morphology, and the thickness of the absorption layer and of the window layer on the dark current, white light photoresponse and ultraviolet photoresponse. The epitaxial layers were grown on double polished c-plane (0001) sapphire substrates to allow for back-side illumination. The PIN photodiode structures typically consist of a 0.8 μm-thick $Al_{0.60}Ga_{0.40}N$ "window" layer, graded to a 0.2 μm-thick $Al_{0.45}Ga_{0.55}N$ *N* layer, a 0.15 μm-thick $Al_{0.30}Ga_{0.70}N$ *I* layer, a 0.2 μm-thick $Al_{0.45}Ga_{0.55}N$ *P* layer, and capped with a 25 nm GaN:Mg contact layer. At a 0V bias, the processed PIN devices exhibit a solar-blind photoresponse having a maximum responsivity of 0.053 A/W at 267 nm, corresponding to an external quantum efficiency of ~25%, uncorrected for reflections, etc. The MSM devices typically consist of an AlGaN x~0.6 window layer, and an undoped AlGaN x~0.45 absorbing layer. The MSMs exhibit an external quantum efficiency has high as ~48% at a bias of 15V with a peak response at 265nm. The noise characteristics and speed of response for these devices are also excellent. These devices exhibit high values of

detectivity (D*) and are suitable for the fabrication of back-illuminated solar-blind imaging photodetector arrays.

11:30 AM I12.10
GROWTH AND CHARACTERIZATION OF Al RICH AlGaN ALLOYS AND AlGaN/GaN HETEROSTRUCTURES. H.X. Jiang, J. Li, K.H. Kim, K.B. Nam, and J.Y. Lin, Department of Physics, Kansas State University, Manhattan, KS.

Although many of the ideas and potentials of III-nitride devices for UV applications have been identified, a transition from basic research to practical device components has not yet been made due to various technological obstacles. Several key issues must be resolved. For example, so far blue emitters based III-nitrides exploit InGaN/GaN QWs as active media. In order to achieve UV emitters, higher bandgap materials such as AlGaN/GaN QWs with high Al contents must replace the InGaN/GaN active region. However, very little work has been done so far for $Al_xGa_{1-x}N$/GaN QWs with high Al content (x > 0.5). On the other hand, the use of high Al-content AlGaN layer is expected to increase the overall figure of merit of the AlGaN/GaN HFETs due to the combined advantages of enhanced band offset and lattice mismatch-induced piezoelectric field, both of which are known to provide higher two-dimensional electron gas (2DEG) densities in the channel. We report here the growth and characterization of Al rich (x > 0.5) $Al_xGa_{1-x}N$ alloys, $Al_xGa_{1-x}N$/GaN heterostructures, and $Al_xGa_{1-x}N$/GaN QWs. For Al-rich AlGaN alloys, both Si and Mg doped epilayers have been obtained. From the measured resistivity as a function of Al content data for Mg-doped AlGaN alloys, a relation between Mg activation energy and Al content has been deduced, from which the mechanisms for low conductivity of p-type AlGaN may be understood. In order to probe the optical quality of Al rich (x > 0.5) $Al_xGa_{1-x}N$ alloys and QWs, a special deep UV (up to 6.2 eV) femtosecond laser system, which consists of a Ti:sapphire laser and a frequency quadrupler, was also designed to study their time-resolved photoluminescence (PL) properties. When the growth conditions were optimized, AlN/GaN MQWs emit two PL bands in the deep UV region corresponding respectively to the interband optical transitions of electrons and holes in the n=1 and n=2 subbands in the wells, E11 and E22, from which the conduction band offset for the GaN/AlN heterojunction was deduced to be about 70%. The transport properties of Al-rich AlGaN/GaN HFET structures have been studied by varying the growth conditions and structural parameters, including Si-doped AlGaN barrier thickness, i-AlGaN spacer layer thickness, and Si doping concentration. It was shown that Al rich AlGaN/GaN heterostructures could supply higher sheet densities (around 10^{14} cm^{-2}, which can have many applications for high power electronic devices.

11:45 AM I12.11
IMPROVED MOBILITIES AND RESISTIVITIES IN MODULATION DOPED P-TYPE AlGaN/GaN SUPERLATTICES. Erik L. Waldron, John W. Graff, E. Fred Schubert, Boston University, Department of Physics and Electrical and Computer Engineering Department, Boston, MA.

P-type $Al_xGa_{1-x}N$/GaN superlattice structures have demonstrated higher acceptor activation due to a modulated valence band resulting from the superlattice as well as spontaneous and piezoelectric polarization fields. The polarization effects are due to the wurtzite structure of $Al_xGa_{1-x}N$ and the strain present in $Al_xGa_{1-x}N$/GaN heterostructures. Variable temperature Hall effect studies of Mg doped $Al_{0.20}Ga_{0.80}N$/GaN $100Å/100Å$ superlattices reveal an improvement in resistivity and mobility for modulation doped structures versus a uniformly doped structure. Very low resistivities less than 0.1 Ω cm and hole mobilities ~36 cm^2/V s are demonstrated. This improvement is attributed to a reduction of neutral and ionized impurity scattering for the two-dimensional hole gas present in the gallium nitride layers of the modulation doped superlattice. The improvement is greatest at temperatures below ~150 K. The doped regions of the superlattices have magnesium concentrations of ~10^{19} cm^{-3}. Two modulation doped samples were grown by MBE: a standard scheme with dopants only in the AlGaN barriers, and a shifted scheme with dopants concentrated near the AlGaN/GaN interfaces. The standard sample has mobilities of 9.2 and 36 cm^2/V s at 300 and 90 K, respectively. Resistivities of the standard sample are 0.20 and 0.068 Ω cm at 300 and 90 K, respectively. Carrier concentrations for this sample are 3.3 and 2.5×10^{18} cm^{-3} at 300 and 90 K, respectively. Capacitance-voltage profiling on one of the samples shows a clear indication of a two-dimensional hole gas as well as the periodicity of the superlattice.

SESSION I13: PROCESSING
Chair: David C. Look
Friday Afternoon, November 30, 2001
Room 302 (Hynes)

1:30 PM I13.1
TRANSPARENT ZnO-BASED OHMIC CONTACT TO p-GaN. E. Kaminska, A. Piotrowska, K. Golaszewska, M. Guziewicz, A. Kudla, A. Barcz, Institute of Electron Technology, Warsaw, POLAND; M. Zielinski, M. Aleszkiewicz, Institute of Physics PAS, Warsaw, POLAND; E. Litwin-Staszewska, High Pressure Research Centre, Warsaw, POLAND; J. Jasióski, Z. Liliental-Weber, Lawrence Berkeley National Laboratory, Berkeley, CA.

In a variety of applications, such as light-emitting, -detecting and -triggered semiconductor devices the top electrode functions both as ohmic contact and optical window. GaN-based photonic devices, hindered by well-known p-type doping problem, use almost exclusively a very thin (~10nm) oxidised Ni/Au contact as the transparent p-type electrode. Ni/Au metallization however, does not fulfil the prerequisite of thermal stability. In this paper, we report on a new transparent conducting electrode enabling fabrication of high-transmittance, low resistivity ohmic contacts to p-GaN. To this end we use p-type ZnO. This material is an excellent candidate material for a thermally stable heterojunction contact to p-GaN. Similarly to GaN, ZnO is a wide direct gap semiconductor and its crystallographic structure is hexagonal, closely lattice matched to GaN. Up to now however, only a very limited number of reports appeared about the fabrication of p-type ZnO, namely chemical vapour deposition or pulsed laser deposition techniques have been used to grow thin films of p-ZnO, using N or As as acceptors. New idea of this work is to form p-ZnO:N in a two-step process: first, thin film of elemental Zn was deposited on p-GaN substrate by thermal evaporation in high vacuum. Next, Zn film was oxidised in an oxygen flow at a temperature of about 300°C. To incorporate acceptors, a controlled amount of nitrogen was introduced into the vacuum chamber during the deposition of Zn. The electrical and optical properties of thin ZnO films were assessed by measurements of sheet resistance, Hall effect, ellipsometry and photospectrometry. Ohmic contacts were characterised by TLM measurements. The contact microstructure was analysed using secondary ion mass spectrometry, transmission electron microscopy and atomic force microscopy. The above procedure proved successful in fabricating p-ZnO of the resistivity as low as 1×10^{-3}Ωcm and resulted in ohmic contacts with light transmittance of 75% in the wavelength range of 400-700 nm for 55nm thick p-ZnO film, and with the contact resistivity below 1×10^{-3}Ωcm^2.

1:45 PM I13.2
LOW RESISTANCE NON-TRANSPARENT OHMIC Pt-CONTACTS ON P-GaN. Andreas Weimar, Georg Brüderl, Stefan Bader, Volker Kümmler, Alfred Lell, Volker Härle, OSRAM Opto Semiconductors, Regensburg, GERMANY.

The metal - p-GaN junction for low resistance ohmic contacts is still a challange to be applied in GaN-based opto electronics as well as in power and high frequency devices. At OSRAM Opto Semiconductors we are currently working on the realization of blue laser diodes for applications like data storage, printing, projection displays and illumination. In order to decrease heat generation during device operation it is necessary to ensure as small contact resistances as possible. In this work, we achieved a best value for Pt-contacts of 2,5 ± 1,8•10^{-5} Ωcm^2 which to our knowledge is one of the lowest reported specific contact resistances on MOVPE-grown p-GaN. The Pt-layers were deposited by e-beam and thermal assisted vacuum evaporation after a standard cleaning process. For evaluation of R_c we used optimized circular TLM test patterns defined by photolithography. The best contacts were formed by annealing in nitrogen at 500°C. We also investigated the dependance of the contact resistance on the Mg doping concentration. Therefore, p-GaN layers with different Mg-concentrations were grown on SiC-substrates and Pt-contacts were processed. For those samples we got experimental results concerning the Mg-concentrations verified by secondary ion mass spectroscopy (SIMS), the hole concentrations and mobilities, which we received from HALL-measurements and the contact and sheet resistivities investigated by circular TLM measurements. The influence of self-compensation effects in p-GaN near surfaces and in bulk will be discussed.

2:00 PM I13.3
NON ALLOYED Ti/Al/Ni/Au OHMIC CONTACT FORMATION TO *n*-GaN. P. Schlotter, R. Schmidt, W. Pletschen, S. Klussmann, H. Obloh, Fraunhofer-Institut für Angewandte Festkörperphysik, Freiburg, GERMANY.

The specific contact resistance as well as the reproducibility and long term stability of ohmic contacts affect the reliability of GaN devices. Among a variety of single and multilayer metallizations Ti/Al/Ni/Au is widely used for *n*-contacts to *n*-GaN. Up to now most of the work on *n*-contacts has been done on metallization deposited on as-grown *n*-GaN. For the fabrication of optoelectronic devices on insulating substrates such as sapphire the *n*-metallization has to be deposited on etched *n*-GaN. To obtain ohmic contacts with a low specific resistance

the contacts are usually annealed at temperatures above 500°C inducing an interdiffusion of the metallic compounds. This causes a high surface roughness and a spiky interface which will reduce the reliability of the device. In this work we have investigated the resistance of non alloyed Ti/Al/Ni/Au ohmic contact metallization to CAIBE etched n-GaN. The effects of surface annealing prior to contact deposition were studied by measuring the specific contact resistance by the transmission line method (TLM). While unannealed Ti/Al/Ni/Au contacts to untreated dry etched n-GaN surfaces show a specific contact resistance of 1×10^{-4} Ωcm^2 and a non ohmic I-V characteristic, unannealed Ti/Al/Ni/Au contacts to 600°C annealed n-GaN surfaces are ohmic and have a specific contact resistance as low as 7×10^{-5} Ωcm^2. The resistance can be further reduced to $< 10^{-5}$ Ωcm^2 by annealing the etched n-GaN surface in an oxygen containing atmosphere before contact deposition. In contrast to conventionally annealed Ti/Al/Ni/Au contacts these unannealed contacts show a smooth and homogeneous surface as well as a good adhesion while the specific contact resistance is in the same order of magnitude as that of annealed contacts. Possible mechanisms reducing the specific contact resistivity by surface annealing are discussed.

2:15 PM I13.4
X-RAY PHOTOEMISSION DETERMINATION OF THE SURFACE FERMI LEVEL MOTION AND PINNING ON n- AND a-GaN DURING THE FORMATION OF Au, Ni AND Ti METAL CONTACTS. Kimberly A. Rickert, University of Wisconsin-Madison, Department of Chemistry, Madison, WI; Jong Kyu Kim, Pohang University of Science and Technology, Department of Materials Science and Engineering, Pohang, KOREA; Jong-Lam Lee, Pohang University of Science and Technology, Department of Materials Science and Engineering, Pohang, KOREA; Franz J. Himpsel, Department of Physics, University of Wisconsin-Madison, Madison, WI; Arthur B. Ellis, Department of Chemistry, University of Wisconsin-Madison, Madison, WI; Thomas F. Kuech, Department of Chemical Engineering, University of Wisconsin-Madison, Madison, WI.

One challenge in GaN device fabrication, for either electronic or optical applications, is the development of low resistance ohmic contacts to both n- and p-type materials. This study focuses on the basic formation of metal contacts in the very early stages of contact development. Both n-GaN and p-GaN samples are studied prior to metal deposition via synchrotron radiation-based x-ray photoemission spectroscopy. The Ga 3d core level and valence band spectra are acquired. Sub-monolayer amounts of Au, Ti or Ni are used to study initial stages of contact formation. The Ga 3d core level and Fermi edges of the metal are acquired. From these data the position and movement of the surface Fermi level are established, as well as the surface Schottky barrier height of the n-GaN and p-GaN samples. The contributions of non-equilibrium effects, such as resistive voltage drops and surface photovoltages, were found and used to obtain accurate surface Fermi level positions. For Au and Ti the surface Fermi level determined with these corrections lies at different positions within the gap on n- and p-type materials at thick metal coverages suggesting separate acceptor-like and donor-like mid-gap states. For Ni, p- and n-type pinning positions nearly coincide indicating a continuum of mid-gap pinning states.

2:30 PM I13.5
MECHANISMS OF GALLIUM NITRIDE SEPARATION FROM SAPPHIRE BY LASER LIFT-OFF. Y. Cho, A. Salleo, T. Sands, Dept of Materials Science & Engineering, University of California-Berkeley, Berkeley, CA; N. Cheung, Dept of Electrical Engineering and Computer Sciences, University of California-Berkeley, Berkeley, CA; G. Solomon, CBL Technologies, Inc., Redwood City, CA; E.A. Stach, National Center for Electron Microscopy (NCEM), Lawrence Berkeley National Laboratory, Berkeley, CA; W.S. Wong, M. Kneissl, Xerox Palo Alto Research Center, Palo Alto, CA.

The separation of a GaN film from its sapphire growth substrate by a UV laser induced lift-off process allows the transfer of heterostructure LEDs and laser diodes to virtually any substrate, the fabrication of vertical GaN-based laser cavities, and the production of GaN substrates (from thick HVPE GaN films). Although the laser lift-off (LLO) process has been incorporated into the fabrication of the numerous novel device structures, the current understanding of the process is in its infancy. A mechanistic and predictive understanding would allow the full exploitation of LLO as a high-throughput and reliable manufacturing process. In this study, the lift-off mechanisms of both MOCVD GaN and HVPE GaN films were analyzed based on a model combining thermoelastic strain energy release and thermo-chemical decomposition. HVPE GaN films were found to separate after exposure to a single 38 ns excimer laser pulse of fluence 390 mJ/cm^2 whereas MOCVD films required 560 mJ/cm^2. The MOCVD films with a flatter interface and lower defect density were separated by homogeneous thermochemical decomposition at the GaN/sapphire interface, resulting in a high density of Ga metal islands at the interface. In contrast, the separation of the HVPE GaN films at a lower fluence can be attributed to interfacial fracture driven by strain energy release and initiated by the thermochemical decomposition of pockets of amorphous material at the GaN/sapphire interface. The authors at UC Berkeley acknowledge support from NSF (DMI-0088145).

2:45 PM I13.6
DEEPLY UNDERCUT ETCHING FOR GaN/$In_xGa_{1-x}N$/GaN HETEROSTRUTURE BY FRONTSIDE-ILLUMINATED PHOTOELECTROCHEMICAL WET ETCHING. Yan Gao[a], Andreas R. Stonas[b], Ilan Ben-Yaacov[b], Umesh Mishra[b], Steve P. DenBaars[a,b], Evelyn L. Hu[a,b], [a]Materials Dept., University of California, Santa Barbara, CA; [b]Electrical and Computer Engineering Dept., University of California, Santa Barbara, CA.

Wet Photoelectrochemical (PEC) etching has been shown to be an effective means of obtaining low-damage, rapid etching of GaN-based materials. In particular, the doping-dependent and bandgap-dependent nature of PEC etching can be used to form three-dimensional device structures through the selective etching of particular layers in a heterostructure material. We have recently formed GaN cantilevers through a combination of illumination through the sapphire substrate (backside illumination) and selective removal of a lower bandgap InGaN sacrificial layer. Backside illumination is well suited for cantilever fabrication, and for achieving lift-off of GaN devices from their starting substrate. Certain applications, however, would benefit from undercut profiles achieved through illumination from the frontside: there is then greater control of the alignment of various critical device components. This paper will report on the use of frontside illumination to form controlled, undercut etching of GaN/$In_xGa_{1-x}N$ /GaN heterostructures. The samples used in this study are MOCVD-grown (uid)GaN/$In_xGa_{1-x}N$/(uid)GaN heterostructures (x~0.056-0.08, 600Å thick $In_xGa_{1-x}N$ layer, 1μm thick top GaN layer). 200Å Ni/1000Å Au layers formed the masking patterns for the PEC etching, which was carried out using a 2.2 M solution of KOH, with illumination from a Xe lamp. n-GaN-on-sapphire, interposed between the lamp and the sample, filtered out the shorter wavelength components of the Xe lamp, to achieve selective etching of the lower bandgap InGaN. We will report on the change in etch rate and etch morphology with changes in illumination intensity and the electrical bias of the sample. We have been able to achieve lateral etch rates greater than 10μm/minute with a smooth etched surface. We believe that this technique may have important applications in the formation of apertured structures for electronic and optical devices.