# SYMPOSIUM W

## GaN and Related Alloys

November 28 – December 3, 1999

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# TUTORIAL

**FTW: MATERIAL CHARACTERISTICS OF THE III-NITRIDES**
**Sunday, November 28, 1999**
**2:00 - 5:00 p.m.**
**Room 202 (H)**

Our understanding of the properties of the III-nitrides continues to grow at a rapid rate due to world-wide interest in developing these materials for semiconductor device applications. This interest has resulted in systematic efforts to synthesize bulk materials and to characterize their mechanical and electronic properties. The last three years have seen a much better understanding of band structure, defect structures, thermal expansion coefficients, non-linear optical coefficients, piezo-electric, pyroelectric, thermal conductivity, and other important properties that are needed for manufacturing devices and understanding their performance. This tutorial will bring together the latest information on these topics. Substantial new efforts have been made to produce bulk crystals of the III-nitrides, which have allowed much more thorough material characterization to be carried out. The tutorial will also include some discussion of what controversies remain.

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SESSION W1: OPTICAL DEVICES
Chair: Isamu Akasaki
Monday Morning, November 29, 1999
Room 302 (H)

**8:30 AM *W1.1**
HIGH POWER InGaN-BASED LASER DIODES WITH AN OUTPUT POWER OF 30 mW. Shuji Nakamura, Nichia Chemical Industries Ltd, Dept of R&D, Anan, Tokushima, JAPAN.

A violet InGaN multi-quantum-well (MQW)/GaN/AlGaN separate-confinement-heterostructure laser diode (LD) was grown on epitaxially laterally overgrown GaN on sapphire. The LDs with cleaved mirror facets showed an output power as high as 40 mW under room-temperature continuous-wave (CW) operation. The stable fundamental transverse mode was observed at an output power of up to 40 mW. The smallest aspect ratio of the far-field pattern was 1.6. The wavelength drift caused by the temperature change was estimated to be 0.06 nm/K. The lifetime of the LDs at a constant output power of 5 mW was more than 1,900 hours under CW operation at an ambient temperature of 50°C. That at a constant output power of 30 mW was more than 400 hours under CW operation at an ambient temperature of 60°C.

**9:00 AM *W1.2**
ROOM TEMPERATURE CW OPERATION OF GaN-BASED BLUE LASER DIODES. Masayoshi Koike, Shiro Yamasaki, Yuta Tezen, Seiji Nagai, Sho Iwayama, Akira Kojima, Toyoda Gosei Co., Ltd, Optoelectronics, Aichi, JAPAN.

Recently, continuous wave (CW) operation of GaN-based blue laser diodes (LDs) have been achieved at room temperature by several groups. The conventional GaN-based LD structures were GaInN multiple quantum wells (MQWs)-separate confinement heterostructure (SCH) using GaN optical-guiding layer. A refractive index of GaN was smaller than that of GaInN, and, therefore, an optical confinement factor of GaInN optical-guiding layer was superior to that of GaN. We have applied GaN/GaInN optical-guiding layers to GaInN/GaN MQW-SCH LD, in order to reduce a threshold current (Ith) compared with that of GaN optical-guiding layer. The SCH LD structure were n-GaN/n-$Ga_{1-x}In_xN$ optical-guiding layer, the active layer having three GaInN QWs and p-$Ga_{1-x}In_xN$/p-GaN optical-guiding layer grown on an a-faced sapphire substrate by MOCVD. The facets were formed by Ar-$Cl_2$ reactive ion beam etching (RIBE). The GaN/GaInN optical-guiding layer reduced the threshold current to almost half of GaN optical-guiding layer, and its room temperature CW operation were realized at 410 nm of lasing wavelength.

**9:30 AM W1.3**
IMPROVED CHARACTERISTICS OF InGaN MULTI-QUANTUM WELL LASER DIODES GROWN ON LATERALLY OVERGROWN GaN ON SAPPHIRE. Monica Hansen, Paul Fini, Lijie Zhao, Amber Abare, James S. Speck, Larry A. Coldren, and Steven P. DenBaars, Materials Department and Electrical and Computer Engineering Department, University of California, Santa Barbara, CA.

InGaN-based laser diodes have potential in a number of applications such as optical storage, printing, full-color displays, chemical sensors and medical applications. Major developments in recent years have led to lifetimes in excess of 10,000 hours, demonstrating the viability of nitride laser diodes for commercial applications. These long lifetimes were not achieved until lasers were grown on lateral epitaxial overgrown (LEO) GaN, which reduces the dislocation density from $\sim 10^9$ $cm^{-2}$ to $\sim 10^5$ $cm^{-2}$. The reverse bias leakage current is reduced by 3 to 4 orders of magnitude for devices on LEO GaN region as compared to devices on the defected GaN region, showing that dislocations contribute to leakage current. InGaN multi-quantum well (MQW) laser diodes have been fabricated on fully coalesced laterally overgrown GaN on sapphire. The threshold current density was reduced by a factor of 2 from 10 $kA/cm^2$ for laser diodes grown on sapphire substrates to 4.8 $kA/cm^2$ for laser diodes grown on LEO GaN on sapphire. The lasers on the LEO GaN showed this low threshold current density both above the $SiO_2$ mask regions and above the merge fronts of the overgrown GaN. This reduction in threshold current density is attributed to a reduction in nonradiative recombination and loss due to the lower dislocation density in the LEO GaN. The L-I characteristics were measured for different temperatures, yielding a characteristic temperature of 120 K. The laser diodes continued to lase under pulsed operation at a temperature of 120°C, which is among the highest reported. The structural properties of the laser structure on LEO have been characterized by transmission electron microscopy (TEM), atomic force microscopy (AFM) and x-ray diffraction. The tilt of the wing regions was measured by x-ray diffraction to be 0.1° compared to tilts commonly seen, which are greater than 1°. The laser structures on LEO have a reduced dislocation density compared to those grown on sapphire substrates. TEM and AFM micrographs show that the wing regions as well as the coalescence regions contain few or no threading dislocations.

**9:45 AM W1.4**
EFFECT OF AlGaN/GaN STRAINED LAYER SUPERLATTICE PERIOD ON InGaN MQW LASER DIODES. M. Hansen, A.C. Abare, P. Kozodoy, T.M. Katona, M.D. Craven, J.S. Speck, U.K. Mishra, L.A. Coldren and S.P. DenBaars, Materials Department and Electrical and Computer Engineering Department, University of California, Santa Barbara, CA.

Recent research advances have resulted in GaN-based laser diode lifetimes in excess of 10,000 hours, demonstrating that commercial production of these devices for optical storage, printing, chemical sensing, and full-color display applications may soon be realized. A key issue in the evolution of GaN-based devices is the development of high quality p-type layers. This work investigates AlGaN/GaN strained layer superlattices used as cladding layers in InGaN multiple quantum well (MQW) lasers grown via metalorganic chemical vapor deposition (MOCVD). Superlattices are advantageous since they provide strain relief within the laser structure as compared to bulk AlGaN cladding layers, and p-type superlattices have recently demonstrated enhanced hole concentration. The structural quality of laser diodes with AlGaN/GaN superlattice claddings was superior compared to a laser structure with a bulk AlGaN cladding as seen by atomic force microscopy (AFM) and x-ray diffraction (XRD). The superlattice claddings have reduced edge dislocation densities, indicating the improved crystal quality of superlattice claddings over bulk claddings. The corresponding laser diode characteristics also reflect the influence of the superlattice claddings and the effects of superlattice period on device performance. The DC voltage of the diodes increases with increasing superlattice period and is significantly higher for the bulk cladding. Additionally, the threshold voltage follows the same trend as the DC voltage, increasing from 16 to 25 V due to the lower probability of holes tunneling through the thicker AlGaN layers of larger period superlattices. The threshold current density also increases with increasing superlattice period from 8.4 to 13.2 $kA/cm^2$. Transmission line model (TLM) measurements revealed an increase in lateral conductivity with superlattice period which leads to increased carrier recombination at the sidewalls of the laser ridge, thus reducing threshold current density.

**10:30 AM W1.5**
FABRICATION AND CHARACTERIZATION OF III-NITRIDE MICRODISK-CAVITY LIGHT-EMITTING-DIODES. J.Y. Lin, S.X. Jin, J. Li, K.C. Zeng, J.Z. Li, and H.X. Jiang, Department of Physics, Kansas State University, Manhattan, KS.

Microdisk- and microring-cavity light-emitting-diodes (LED) have been fabricated from metal-organic chemical-vapor deposition (MOCVD) grown p-n junctions and InGaN/GaN quantum wells. Photolithographic patterning and inductively-coupled plasma (ICP) dry etching have been employed to create theses devices. Device characteristics, such as the current versus voltage (IV) and light output versus current (LI) characteristics and electro-luminescence

(EL) spectra have been measured and compared with those of conventional broad-area LEDs. Our preliminary results have shown that the quantum efficiencies of the microdisk- and microring-cavity LEDs are significantly enhanced over the conventional broad-area LEDs, due to the micro-size effects. Additionally, a factor of 6 enhancement in the current density has also been observed in the microdisk-cavity LEDs. The EL emission properties under electrical carrier injection are compared with the photoluminescence properties obtained under optical carrier injection. The emission mechanisms and recombination dynamics in these micro-LEDs have been investigated. Our results suggest that for a fixed luminous area, the total light output can be enhanced by replacing the conventional broad-area LEDs with the micro-size LED arrays. Optical pumping was also employed to study the optical confinement effects in III-nitride microdisk and microring cavities prior to the contact fabrication. When an individual disk or ring is optically pumped, resonance modes corresponding to the radial and the whispering-gallery (WG) modes were simultaneously present in microdisk cavities, but only WG modes were available from the microring cavities. The implications of our results on the design of future UV/blue micro-optoelectronic devices such as micro-LEDs, micro-LED arrays for micro-size display, and micro-vertical-cavity LEDs, microdisk and microring laser diodes, and will be discussed.

**10:45 AM W1.6**
SPATIALLY RESOLVED ELECTROLUMINESCENCE OF InGaN-MQW-LEDS. Veit Schwegler, Christoph Kirchner, Matthias Seyboth, Markus Kamp, University of Ulm, Dept. of Optoelectronics, Ulm, GERMANY; Peter Fischer, Jürgen Christen, Margit Zacharias, Otto-von-Guericke University, Institute of Experimental Physics, Magdeburg, GERMANY.

Electroluminescence (EL) is the most significant measure for light-emitting diodes (LEDs) since it probes the relevant properties of the fully processed device under operation. In addition to conventional spectrally resolved EL, scanning micro-EL provides spatially resolved information (i.e. wavelength, intensity, linewidth, etc.) and a direct correlation of morphological and optical properties at the same sample position. The devices under investigation are InGaN multi-quantum well LEDs grown by MOVPE on sapphire substrates. Single peak band-band emission at about 410 nm is observed for the integral EL, corresponding to an In-contents of approximately 10%. The output power of the UV-LEDs is in the 1 mW range. The $\mu$-EL-characterization is performed as a function of injection current densities and the emission is investigated from the epitaxial layer as well as from substrate side. Spatially resolved wavelength images reveal emission peaks between 406 nm and 417 nm, corresponding either to In fluctuations of 1%-1.5% or local fluctuations of piezoelectric fields. The respective EL intensity distribution shows areas of bright luminescence spreading with increasing current density. However, the wavelength fluctuations are still observed. In the integral spectra a thermally induced redshift of the EL peak from 410 nm to 415 nm is observed towards higher current densities. The wavelength image from the substrate side reveals an additional local redshift to 419 nm of the area beneath the p-contact, caused by heating, thus reflecting the thermal distribution in the device.

**11:00 AM W1.7**
REDUCED TURN-ON VOLTAGE FOR GaN:Er LEDs. J. Heikenfeld, M.J. Garter, D.S. Lee, R. Birkahn, A.J. Steckl, University of Cincinnati, Nanoelectronics Lab, Cincinnati, OH.

We have shown that LEDs based on rare earth (RE) doped GaN emit red (Pr, Eu), blue (Tm) or green (Er) light. REs as dopants in GaN simplify some critical integration problems in the next generation of display and lighting technology. Improvements in overall LED performance and efficiency requires lower power operation while preserving device brightness. We present techniques to lower the GaN:Er LED optical turn-on voltage to under 10V, where we use the term turn-on voltage to signify the LED bias condition when visible emission is first noticeable to the naked eye in normal ambient lighting conditions. The GaN:Er films were grown on Si substrates by MBE with solid sources for Ga and the Er and with a nitrogen plasma source. The GaN:Er LED fabrication utilized transparent In-Sn oxide (ITO) contacts. We have investigated two approaches for reducing the optical turn-on voltage: (a) use of heavily doped ($\sim$0.03 ohm-cm) Si substrates instead of standard ($\sim$10 ohm-cm) wafers; (b) decreasing the GaN layer thickness from the 1000-2000 nm range to the 300-700 nm range. We have found that increasing the Si substrate doping results in a more pronounced rectifying electrical characteristic for the devices. For the thick GaN layers of 1000-2000 nm, this is accompanied by reduction in optical turn-on voltage from a 40-120 V range to 10-15 V for the heavily doped substrates. Further reduction in turn-on voltage was obtained by reducing the GaN:Er layer. For example, a device with only 300 nm film thickness exhibited an optical turn-on voltage of only 6 V. This effect of GaN:Er layer thickness on turn-on voltage was not observed for the standard Si substrates. Reducing the GaN:Er layer thickness also decreased the electrical turn-on voltage, resulting in a higher input power (albeit at a lower voltage) being necessary for optical turn-on. The optimum device structure is likely to be a combination of these two approaches. We conclude that GaN:Er LEDs can be designed with power requirements compatible with drive circuitry utilized in standard junction-based LED display technology.

**11:15 AM W1.8**
HIGH REFLECTANCE NITRIDE DISTRIBUTED BRAGG REFLECTORS GROWN BY MOLECULAR BEAM EPITAXY. Hock Min Ng and Theodore Moustakas, Boston Univ, Dept of Electrical Engineering and Center for Photonics Research, Boston, MA.

Distributed Bragg reflectors (DBRs) are vital for the fabrication of vertical cavity surface emitting lasers (VCSELs) and resonant-cavity light emitting diodes and detectors. The development of nitride-based DBRs will pave the way for entire device structures (active region and mirrors) to be grown monolithically in a single growth run. We have recently reported on AlN/GaN DBRs (20.5 periods) with peak reflectance of 95% at 392nm [1]. The bandwidth was 25nm although the theoretically predicted value is $\sim$50nm based on the refractive index difference of AlN and GaN. Other workers have reported on GaN/AlGaN DBRs with up to 96% reflectance [2,3]. However, due to a smaller refractive index contrast, between 30-35 periods had to be grown to achieve high reflectance. In the present work, we report on AlN/GaN DBRs with peak reflectance of 99% at 465nm utilizing 20.5 periods. By improving the control of quarterwave layer thicknesses, a bandwidth of 45nm was realized. However, portions of the wafer show a network of cracks on the surface which is attributed to the tensile stress built up in the AlN layers. Assymetrical structures with AlN layers thicker than a quarterwave and GaN layers thinner than a quarterwave have been grown and were crack-free. Simulation and experimental data show that high reflectance is still possible although the bandwidth is slightly reduced. [1] H.M. Ng, D. Doppalapudi, E. Iliopoulos and T.D. Moustakas, Appl. Phys. Lett. 74, 1036 (1999). [2] T. Someya and Y. Arakawa, Appl. Phys. Lett. 73, 3653 (1998). [3] R. Langer, A. Barski, J. Simon, N.T. Pelekanos, O. Konovalov, R. Andre and L.S. Dang, Appl. Phys. Lett. 74, 3610 (1999).

**11:30 AM W1.9**
HIGH-SENSITIVITY VISIBLE-BLIND AlGaN HETERO-STRUCTURE PHOTODIODES. J.D. Brown, Zhonghai Yu, C. Boney, M.A.L. Johnson, J.W. Cook, Jr., and J.F. Schetzina, Dept of Physics, North Carolina State University, Raleigh, NC.

The successful synthesis, fabrication, and testing of two types of AlGaN heterojunction p-i-n photodiodes that operate in the range from 280-365 nm is reported. The first type consists of a 1.5 $\mu$m $Al_{0.2}Ga_{0.8}N$:Si n-type layer grown by MOVPE onto a low temperature AlN buffer layer on sapphire. On top of this is a 0.2 $\mu$m undoped i-GaN active layer followed by a 0.5 $\mu$m p-type GaN:Mg layer. The second type of diode consists of a 1.5 $\mu$m thick n-type $Al_{0.33}Ga_{0.67}N$:Si layer, followed by a 0.2 $\mu$m undoped i-$Al_{0.16}Ga_{0.84}N$ active layer and a 0.5 $\mu$m p-type $Al_{0.16}Ga_{0.84}N$:Mg top layer. Square mesas of area A = 4 x $10^{-4}$ $cm^2$ were obtained by reactive ion etching using $BCl_3$. Ti/Al and Ni/Au were used for n-type and p-type metal contacts, respectively. Photodiode spectral responsivities R were measured under zero-bias at 300K for the wavelength range 200 to 500 nm with the devices illuminated through-the-substrate. $R_0A$ values were also obtained for each sample. The detector spectral detectivity D* was then calculated using standard photodiode equations for a noise-limited detector. The GaN/ $Al_{0.2}Ga_{0.8}N$ photodiodes exhibited a UV spectral response between 320 and 365 nm. Peak responsivity R = 0.21 A/W occurred at 356 nm, corresponding to an internal quantum efficiency of 82%. $R_0A$ values up to 1.5 x $10^9$ $\Omega$-$cm^2$ were obtained, corresponding to D* = 6.1 x $10^{13}$ cm $Hz^{1/2}$ $W^{-1}$ at 356 nm. This is the largest D* value ever obtained for any semiconductor photodetector at any wavelength and temperature, and is within a factor of six of D* values for UV-enhanced photomultiplier tubes. The $Al_{0.16}Ga_{0.84}N/Al_{0.33}Ga_{0.67}N$ p-i-n photodiodes exhibited a UV spectral response between 280 and 320 nm with a peak spectral responsivity R = 0.09 A/W occurring at 305 nm, corresponding to an internal quantum efficiency of 42%. $R_0A$ values of 2.8 x $10^8$ $\Omega$-$cm^2$ were obtained such that D* = 1.6 x $10^{13}$ cm $Hz^{1/2}$ $W^{-1}$ at 305 nm for this second type of UV detector. At wavelengths >400 nm the responsivity of both types of UV photodiodes is less than $10^{-4}$ A/W. This work is supported by grants from DARPA and ARO.

**11:45 AM W1.10**
LOW-INTENSITY UV PHOTODETECTORS BASED ON HIGH QUALITY AlGaN USING LOW-TEMPERATURE AlN INTERLAYER. Motoaki Iwaya, Nobuaki Hayashi, Takayuki Kashima, Dept of Electrical and Electronic Engineering, Meijo University, Nagoya, JAPAN; Theeradetch Detchprohm, High Tech Research Center, Meijo University, Nagoya, JAPAN; Hiroshi Amano, Isamu

Akasaki, Dept of Electrical and Electronic Engineering and High Tech Research Center, Meijo University, Nagoya, JAPAN; Akira Hirano, Research and Development Department, Osaka Gas Co. Ltd. Kyoto, JAPAN; Cyril Pernot, Research and Development Department, Osaka Gas Co. Ltd. Kyoto, JAPAN, Invited researcher from Groupe d'Etude des Semiconducteurs, Universite Montpellier II, Montpellier, FRANCE.

Multiple low temperature interlayer technique is applied for the growth of $Al_xGa_{1-x}N$ films. When $Al_xGa_{1-x}N$ is directly grown on sapphire covered with a low temperature deposited buffer layer, their crystalline quality becomes progressively worsens with increase of the AlN molar fraction. On the contrary, when growth is carried out on a low-temperature interlayer deposited on GaN, thick and crack-free $Al_xGa_{1-x}N$ films with the entire compositional range having a crystalline quality comparable to that of GaN can be obtained. Threading dislocation (TD) density is lower than $10^9 cm^{-2}$ for all compositional range, which is to the best of our knowledge, the lowest TD $Al_xGa_{1-x}N$ ever reported. These films showed superior optical properties, such as nearly bandedge exciton emission at room temperature and very sharp cut off of the absorption edge. We have fabricated high-sensitivity UV photodetectors based on these films. The detectors showed dark current below 100 fA at 10 V bias allowing a photocurrent to dark current ratio greater than one even under a very low illumination of 40 $nW/cm^2$. They also achieved a rejection ratio of 3 orders of magnitude above and below bandedge, from 200 nm to 360 nm depending on alloy composition of the film. Details will be presented.

SESSION W2/O1: JOINT SESSION:
LATERAL EPITAXIAL OVERGROWTH
Chair: Colin E.C. Wood
Monday Afternoon, November 29, 1999
Room 302 (H)

**1:30 PM *W2.1/O1.1**
PENDEO-EPITAXIAL GROWTH OF GaN AND RELATED MATERIALS ON 6H-SiC(0001) AND Si(111) SUBSTRATES AND THEIR CHARACTERIZATION. Robert F. Davis, T. Gehrke, Kevin J. Linthicum, E.P. Carlson, P. Rajagopal, E.A. Preble, D L. Nida, C.A. Zorman* and M. Mehregany*, Department of Materials Science and Engineering, North Carolina State University, Raleigh, NC; *Department of Electrical, Systems and Computer Engineering and Science, Case Western Reserve University, Cleveland, OH.

Pendeo (from the Latin: to hang or be suspended from)-epitaxy (PE) is a method of growing large area thin films with a low-defect density. It incorporates mechanisms of growth exploited by conventional lateral growth processes by using masks to prevent vertical propagation of threading defects, and extends the phenomenon to employ the substrate itself as a pseudo-mask. The growth does not initiate through open windows, rather it begins on sidewalls of forms etched into a seed layer and continues until coalescence over and between the seed structures occurs, resulting in a single complete layer. The PE growth of GaN and AlGaN alloys via MOVPE and the use of silicon nitride and nickel etch masks has been the focus of this investigation. The three main stages of PE growth, namely (i) initiation of selective lateral homoepitaxy from the seed sidewalls of the nitrides, (ii) vertical growth and (iii) lateral growth over the silicon nitride masked seed structure to form both discrete microstructures and coalesced single crystal layers will be described for these materials. These processing procedures and the aforementioned stages be accompanied in this presentation by supporting structural, microstructural, optical and electrical evidence.

**2:00 PM W2.2/O1.2**
HIGH-QUALITY COALESCENCE OF LATERALLY OVERGROWN GaN STRIPES WITH LOW WING TILT. P.T. Fini, L. Zhao, B. Moran, M. Hansen, H. Marchand, J.P. Ibbetson, S.P. DenBaars, U.K. Mishra, J.S. Speck, Dept. of Materials Science and Dept. of Electrial and Computer Engineering, University of California, Santa Barbara, CA.

Despite recent demonstrations of improved device performance on laterally epitaxially overgrown (LEO) GaN compared to conventional GaN films on sapphire, difficulties remain in controlling the structural quality of the overgrown material during coalescence between neighboring features (*e.g.* stripes). In the LEO of GaN from $<1\bar{1}00>_{GaN}$ or $<11\bar{2}0>_{GaN}$-oriented stripes, it has been observed that the 'wings' (laterally overgrown GaN) exhibit tilts away from the 'window' (seed) regions, in an azimuth perpendicular to the stripe direction. These tilts, often greater than 1°, may be readily observed as a splitting of the $\omega$ rocking curve about the central (window GaN) 0002 peak in x-ray diffraction. In this method, the stripes are aligned such that the scattering plane (defined by incident and diffracted wave vectors) is perpendicular to the $<1\bar{1}00>$ stripe direction. Wing tilt has been correlated with the ratio of wing width (w) to height (h), which is directly dependent on growth conditions (*e.g.* V/III ratio, temperature) and 'fill factor' (the ratio of open width to pattern period). Since wing tilt increases as w/h increases, low wing tilt may be achieved through careful control of the stripe cross-sectional aspect ratio. We have characterized low-tilt LEO GaN stripes grown on large-area (2 inch) $SiO_2/GaN/Al_2O_3$ wafers by low-pressure metalorganic chemical vapor deposition (MOCVD) before and after coalescence. Using scanning electron microscopy (SEM), x-ray diffraction (XRD), trasnsmission electron microscopy (TEM), and atomic force microscopy (AFM), it is shown that by first obtaining wings with low tilt relative to the seed GaN, very few extended defects are formed when wings from neighboring stripes coalesce. After wings with a tilt of $\sim$0.1° are coalesced and an additional $\sim$10 $\mu$m of GaN is grown, it is found with XRD that $\omega$ peak splitting due to tilt is no longer detectable. TEM and AFM results show that few dislocations (with a linear density of $<4x10^3$ $cm^{-1}$) are formed at coalescence fronts.

**2:15 PM W2.3/O1.3**
FABRICATION OF GaN WITH BURIED TUNGSTEN (W) STRUCTURES USING EPITAXIAL LATERAL OVERGROWTH (ELO) AND THEIR CHARACTERIZATION. Kazumasa Hiramatsu, Hideto Miyake, Atsushi Motogaito, Dept of Electrical and Electronic Engineering, Mie Univ, Mie, JAPAN; Yasutoshi Kawaguchi, Shingo Nambu, Nobuhiko Sawaki, Dept of Electronic Engineering, Nagoya Univ, Nagoya, JAPAN; Yasushi Iyechika, Takayoshi Maeda, Sumitomo Chemical Co. Ltd, Tsukuba, JAPAN.

Epitaxial lateral overgrowth (ELO) of GaN with tungsten (W) mask via MOVPE or HVPE is one of the most promising techniques for obtaining not only buried metal structures such as a SIT device but also an ELO-GaN layer with high quality crystalline quality. We will present recent successful results on ELO of GaN with stripe W mask pattern via MOVPE and HVPE. The buried W structure using ELO of GaN is performed by HVPE and a thick buried structure of the W mask with a smooth surface is achieved for the stripe mask patterns along $<11\bar{2}0>$ and $<1\bar{1}00>$. Optical and crystalline characteristics of the ELO-GaN are investigated by means of AFM, CL, TEM and x-ray rocking curve. Thus, those characterizations show evidence of highly crystalline quality with atomically flat surface, uniformly perfect excitonic emission, no c-axis tilting and no small angle grain boundaries, in comparison with a buried structure of $SiO_2$ mask. Furthermore, a thin GaN with buried W structure is achieved by MOVPE for stripe mask pattern $<1\bar{1}00>$. The W has a severe catalytic effect to attack the underlying GaN layer with a hydrogen ambient at a high temperature. To prevent decomposition of GaN layer, we employed ELO of GaN at temperatures below 1000°C under a low reactor pressure ($<$300 or $<$300 Torr)which allows us to enhance the lateral overgrowth. Consequently, the W mask was buried without damage to the underlying GaN and their crystalline and electrical properties and characterized for aiming at the SIT device.

**2:30 PM W2.4/O1.4**
ADVANCED PENDEO-EPITAXIAL GROWTH OF GaN THIN FILMS ON SiC(0001) AND Si(111) SUBSTRATES VIA METALORGANIC CHEMICAL VAPOR DEPOSITION AND THEIR STRUCTURAL, MICROSTRUCTURAL, OPTICAL AND ELECTRICAL CHARACTERIZATION. T. Gehrke, K.J. Linthicum, E.A. Preble, E.P. Carlson, P. Rajagopal and R.F. Davis, Department of Materials Science and Engineering, North Carolina State University, Raleigh, NC.

Growth of GaN thin films with low densities of defects on Si(111) and 6H-SiC(0001) substrates using pendeo-epitaxial (PE) techniques and the characterization of the resulting material are reported. Pendeo-epitaxy is a new form of selective epitaxial growth that is dominated by the growth from sidewalls of rectangular stripes. This process route allows the growth of uniformly low defect density material over the entire surface of the semiconductor. Similar to LEO growth, a mask is employed to prevent vertical propagation of threading dislocations from the GaN seed forms into the regrown areas. The use of a mask can cause the formation of boundaries at the interface of coalescence of two growth fronts and a crystallographic tilt in the adjacent regions that have overgrown the mask. Assemblies of GaN films grown on Si substrates usually show a high density of cracking caused by the difference in the coefficients of thermal expansion of the two materials. Advanced processing routes to achieve PE growth on the aforementioned substrates have been investigated to reduce the formation of coalescence boundaries, the tilt in the overgrown regions, and the cracking in the coalesced GaN films. Microstructural results via transmission electron microscopy and scanning electron microscopy, as well as low temperature photoluminescence and X-ray diffraction spectra, and the data from various electrical investigations have been obtained and will be integrated with the growth results in the presentation and the associated paper.

**2:45 PM W2.5/O1.5**
Abstract Withdrawn.

**3:30 PM W2.6/O1.6**
DISLOCATION MECHANISMS IN THE GaN LATERAL OVERGROWTH BY HYDRIDE VAPOR PHASE EPITAXY. T.S. Kuan, C.K. Inoki, Y. Hsu, D.L. Harris, State Univ of New York at Albany, Dept of Physics, Albany, NY; R. Zhang, S. Gu, T.F. Kuech, Univ of Wisconsin, Dept of Chemical Engineering, Madison, WI.

We have carried out a series of lateral epitaxial overgrowths (LEO) of GaN through thin oxide windows by the hydride vapor phase epitaxy (HVPE) technique under different growth conditions to determine the major factors that govern the dislocation propagation behavior during growth. Electron microscopy and stress simulations are used to investigate the dislocation structure and mechanisms responsible for the tilting of the LEO regions. The growth morphology is most sensitive to the growth temperature. High lateral growth rate at 1100°C allows coalescing of neighboring islands into a continuous and flat film, while the lower lateral growth rate at 1050°C produces triangular-shaped ridges over the growth windows. In either case, threading dislocations bend into laterally grown regions to relax the shear stress developed in the film during the growth. In regions close to the mask edge, where the shear stress is the highest, dislocations interact and multiply into arrays of edge dislocations lying parallel to the growth window. This multiplication and pileup of dislocations, most likely via the Frank-Read type operation, cause a large-angle tilting of the laterally grown regions. The angle of tilt is high($\sim$8 degrees) when the growth is at 1050°C and becomes smaller (3-5 degrees) at 1100°C. At the coalescence of growth facets, a tilt-type grain boundary is formed. During the high-temperature lateral growth, the tensile stress in the GaN seed layer and the thermal stress from the oxide mask layer both contribute to a high shear stress at the growth facets. Finite element stress simulation results indicate that the shear stress close to the oxide mask edge can reach 0.1 GPa or higher, which is sufficient to cause the observed excessive dislocation activities and tilting of LEO regions at high growth temperatures.

**3:45 PM W2.7/O1.7**
GaN LAYERS GROWN BY NANO EPITAXIAL LATERAL OVERGROWTH TECHNIQUE ON POROUS GaN. M. Mynbaeva, A. Titkov, A. Kryzhanovski, A. Zubrilov, V. Ratnikov, V. Davydov, N. Kuznetsov, K. Mynbaev, Ioffe Institute, St. Petersburg, RUSSIA; D. Tsvetkov, S. Stepanov, A. Cherenkov, I. Kotousova, Crystal Growth Research Center, St. Petersburg, RUSSIA; and V. Dmitriev, TDI, Inc., Gaithersburg, MD.

Defect density and stress reduction in heteroepitaxial GaN is one of the main issues in GaN technology. Recently, significant progress in defect density reduction in GaN layers has been achieved using lateral overgrowth technique. In this paper, we describe a novel technique based on nano-scale epitaxial lateral overgrowth (NELOG), for the first time. GaN layers were overgrown by hydride vapour phase epitaxy on porous GaN. Porous GaN was formed by anodization of GaN layers grown previously on SiC substrates. Pore's size was in nano-scale range. It is important that NELOG technique does not require any mask. This technique may be easily scaled for large area substrates. Thickness of overgrown layers ranged from 2 to 70 microns. It was shown that GaN layers overgrown on porous GaN have good surface morphology and high crystal quality. The surface of overgrown GaN material was uniform and flat without any traces of porous structure. X-ray, photoluminescence, and Raman measurements indicated that the stress in the layers grown on porous GaN was reduced down to 0.1 - 0.2 GPa, while the stress in the layers grown directly on 6H-SiC substrates remains at its usual level of about 1 GPa. We propose porous GaN to be used as buffer layer for stress-reduced GaN device structures and bulk material.

**4:00 PM W2.8/O1.8**
LOW DEFECT GaN USING MASS TRANSPORT. Shugo Nitta, Michihiko Kariya, Takayuki Kashima, Shigeo Yamaguchi, Hiroshi Amano and Isamu Akasaki, Dept of Electrical and Electronic Engineering and High-Tech Research Center, Meijo Univ, Nagoya, JAPAN.

Mass transport phenomena and bending of the threading dislocations is observed in GaN for the first time. GaN 7$\mu$m in thickness was grown at 1100°C on a sapphire (0001) substrate using low temperature deposited AlN buffer layer by MOVPE. Squared grooves along [11-20] direction were patterned by RIE. The width and depth of grooves were 3.5$\mu$m and 2.5$\mu$m, respectively. Then, the wafer was annealed at 1000°C in MOVPE reactor with nitrogen and ammonia. During annealing, no group-III alkyl source gas was supplied. After 10 min annealing, most of stripe region were buried by mass transport. TEM observation revealed that defect-free region were formed on the stripe region due to bending of threading dislocations by mass transport. This method is superior to epitaxial lateral overgrowth method because it is mask-free and there is no impurity diffusion from the mask. GaN 3$\mu$m in thickness was continuously grown after mass transport. Above stripe region, defect-free GaN were also grown. Device properties fabricated by using this mass transport method will be shown. This work was partly supported by JSPS.

**4:15 PM W2.9/O1.9**
FORMATION OF GROWTH DOMAINS IN EPITAXIAL LATERAL OVERGROWN GaN ON TUNGSTEN MASKS - DIRECTLY EVIDENCED BY CATHODOLUMINESCENCE MICROSCOPY AND MICRO-RAMAN SPECTROSCOPY. F. Bertram, T. Riemann, D. Rudloff, J. Christen, Inst of Exp Physics, Univ of Magdeburg, GERMANY; A. Kaschner, A. Hoffmann, TU Berlin, GERMANY; K. Hiramatsu, Mie University, Mie, JAPAN.

Employing the technique of epitaxial Lateral Overgrowth (ELO) to the group-III nitrides has been proven successful in significantly reducing the concentration of threading dislocations emanating from the underlying buffer layer. The ELO approach is based on masking parts of the defective crystalline substrate GaN *seed* layer with an amorphous mask layer so that the dislocations are prevented from propagating into the overlayer during subsequent regrowth. However, it is reported that the impurities are unintentional incorporated in the lateral overgrown GaN although the biaxial strain and defect concentration are reduced on the top of the mask. Generally a silicon mask are employed. Epitaxial lateral overgrown GaN structures using tungsten masks oriented in different crystallographic directions ($< 11\bar{2}0 >$ and $< 1\bar{1}00 >$) are comprehensively characterized by scanning cathodoluminescence (CL) microscopy and micro-Raman-spectroscopy. By means of highly spatially resolved CL and $\mu$-Raman investigations, we are able to correlate the optical and structural properties of these ELOG structures on a microscopic scale. Different growth domains are directly imaged. Cross sectional CL microscopy directly visualize the significant differences between the coherently grown seeding regions (between the tungsten-stripes) and the overgrown areas. The overgrown GaN shows a strong blue-shift and broadening of the luminescence, while the CL from the coherent areas is dominated by the strain-shifted narrow ($D^0, X$)-emission. In the CL wavelength image the growth domains of the ELO region are directly identifiable. The micro-Raman measurements show a fundamental other behavior of ELO structures using tungsten mask than using silicon mask. The strain relaxation occurs exponential, however, is not such efficient as with a silicon mask. The overgrown region shows high free carrier concentration, i.e. a strong impurity incorporation.

**4:30 PM W2.10/O1.10**
SELECTIVE AREA GROWTH STUDIES OF COALESCENCE MECHANISMS IN GaN CVD. Michael E. Bartram, Michael E. Coltrin, Christine C. Willan and Jung Han, Sandia National Laboratories, Albuquerque, NM.

In addition to reducing defect concentrations, selective area growth techniques can provide arrays of well-defined GaN islands for studying coalescence mechanisms under carefully controlled conditions. We have used this approach to observe that the intersection of slow growing [11-0n] facets, occurring at the point of convergence between adjacent islands, can open an avenue for growth in the more favorable $< 112 - n >$ crystallographic direction. In this mechanism, growth takes place only a layer at a time in a step-flow fashion on these facets. However, rapid accumulation of these layers can drive growth in the opposing $< 11 - 0n >$ lateral direction as well as the $< 0001 >$ vertical direction at an unexpectedly high rate. These observations explain in molecular terms how rapid surface smoothing of GaN occurs and why this is often observed in the presence of the otherwise slow growing [11-0n] facets in hexagonal pits. Specifically, since nucleation of each layer begins at facet intersections, low surface area facets grow more quickly until adjacent facets have equal areas. This enhancement effect results in pits of high symmetry (hexagonal) during the latter stages of coalescence. (Sandia is operated by Sandia Corporation, a Lockheed Martin Company, for the USDOE under DE-AC04-94AL85000.)

**4:45 PM W2.11/O1.11**
DISLOCATION ARRANGEMENTS IN THICK LEO GaN. K.A. Dunn, S.E. Babcock, D.S. Stone, Materials Science & Engineering Dept, Ling Zhang and T.F. Kuech, Chemical Engineering Dept, University of Wisconsin-Madison, Madison, WI.

Diffraction-contrast transmission electron microscopy and micro-diffraction techniques were used to uncover and characterize dislocation arrangements a thick (15 $\mu$m), coalesced GaN film grown by MOVPE LEO. The windows in the LEO substrate were 1.5 $\mu$m wide with a 12 $\mu$m spacing and their long axis oriented along the $< 1 - 100 >$ direction of underlying GaN on sapphire.

Trimethylgallium (TMGa) and ammonia precursors with a V/III ratio of 1800 were used to grow the film in 2 hours at 1100°C. Under these conditions, the cross-section of the growing GaN prior to coalescence is a beveled rectangle with side walls parallel $\{11-20\}$ and bevels on $\{11-21\}$. As is commonly observed, the threading dislocations that are duplicated from the template above the window bend until they lie parallel to the substrate plane and are annihilated at the coalescence plane. The GaN that grows directly above the window has a lower dislocation density as a result. However, new, dense dislocation complexes that appear to originate from the coalescence plane are generated in the top half of the film. Dislocation loops appear to nucleate at the boundary and extend in a very reproducible pattern into the film a distance that is proportional to the distance of from the substrate. These dislocations first appear about 6 $\mu$m from the substrate, which is also the thickness by which almost all of the original threading dislocations have bent into the (0001) plane. Sets of loops sweep out an approximately triangular bar shaped volume centered on the plane of coalescence. The result is an increasingly higher dislocation density with distance from the substrate and a complex dislocation arrangement in the thick, coalesced GaN film. This work is supported by the ONR MURI on Compliant Substrates at the University of Wisconsin (UW) -Madison. The NSF-MRSEC at UW provides partial support for the UW electron microscopy facilities.

SESSION W3: POSTER SESSION:
GROWTH, STRUCTURAL CHARACTERIZATION,
SURFACE STUDIES, THEORY, DOPING
Chairs: Hiroshi Amano, Randall M. Feenstra,
Thomas H. Myers and Michael S. Shur
Monday Evening, November 29, 1999
8:00 P.M.
Exhibition Hall D (H)

**W3.1**
A TEM STUDY OF GaN GROWN BY ELOG ON 6H SiC.
Pierre Ruterana, Laboratoire d'Etudes et de Recherches sur les Materiaux, UPRESA CNRS 6004, Caen, FRANCE; Bernard Beaumont et Pierre Gibart, Centre de Recherche sur l'Heteroepitaxie et ses Applications, Sophia Antipolis, Valbonne, FRANCE.

The ELOG technique has brought about the possibility to decrease the dislocations densities from 10 10 to less than 10 7 $cm^{-2}$ in GaN layers grown on sapphire. Whereas, the misfit between GaN and 6H-SiC is 3.5% instead of 16% on growth over sapphire, the epitaxial layers have similar densities of defects on both substrates. This has been one of the reason to accept the mosaic growth mode which neither does not provide a sound explanation of the involved mechanisms. It was therefore of interest to investigate layers grown by ELOG in order to identify which dislocations bend and try to understand why. Preliminary observations were carried out on a non completely coalesced layer. They analysed ELOG islands have always the same hexagonal shape, limited by {10-11} facets. It is then pointed out that more than 99% dislocations bend to the basal plane. They have always a $< 1120 >$ character and a very large majority is only of a type. These dislocations are found to fold many times from basal to the prismatic plane, whereas when a+c dislocations bend to the basal plane, they were not seen to come back to a prismatic one.

**W3.2**
SELECTIVE AREA GROWTH TECHNIQUES FOR GaN LEDs.
Koen Jacobs, Jan Cheyns, Ingrid Moerman, Piet Demeester, Dept. of Information Technology, University of Gent, Gent, BELGIUM; Edward J. Thrush, Thomas Swan & Co., Ltd., Harston, Cambridge, UNITED KINGDOM.

Epitaxial Lateral Overgrowth of GaN (ELOG) and Pendeo-Epitaxy (PE) are both promising selective area growth (SAG) techniques for production of low dislocation density GaN, which enables a significant enhancement of (opto)electronic device performance. Recent progress with ELOG has already contributed to the realisation of GaN-based laser diodes with extended lifetime. We already reported on the use of ELOG for violet/blue InGaN/GaN MQW LEDs and currently the comparison with similar LEDs grown on PE is being investigated. Our LEDs on ELOG exhibit the usual leakage current reduction compared to conventional LEDs, but besides this, they also show a two orders of magnitude increase in output power and external quantum efficiency, in contradiction to other reports. Hence, it would be interesting to know if a similar behavior is also retrieved in LEDs on pendeo-epitaxially grown GaN substrates. First results on Pendeo-Epitaxy on sapphire substrates indicated a further structural improvement, since in our case surface morphology and crystalline quality turned out to be better for the PE layers than for the ELOG films. X-ray diffraction was used to probe the material and the corresponding rocking curves showed FWHMs around 200 arcsec, which is a 30% reduction with respect to our ELOG results. PL characterisation gave rise to comparable enhancement of the optical quality. These promising facts, together with the increased PE surface yield, since the use of PE allows a larger surface that is almost dislocation free, suggest that GaN LEDs grown on PE will have better characteristics than LEDs grown on ELOG. Further research is going on to check this statement.

**W3.3**
POLARITY DETERMINATION FOR MOCVD GROWTH OF GaN ON Si (111) BY CONVERGENT BEAM ELECTRON DIFFRACTION.
L. Zhao, H. Marchand, S.P. Denbaars, U.K. Mishra, J.S. Speck, Materials Department and Electrical and Computer Engineering Department, University of California, Santa Barbara, CA.

The growth of GaN on silicon substrate has potential advantages for device integration, thermal management, and economic issues. The lateral epitaxial overgrowth (LEO) of GaN stripes with low dislocation density on Si(111) substrates has recently been demonstrated and the basic structural properties were characterized. The stripe morphology could be controlled by changing the growth temperature or the V/III ratio in a similar way as for LEO GaN on sapphire, which suggested that the polarity of LEO GaN on Si(111) was Ga-face. In this presentation the polarity of laterally overgrown GaN films grown by low-pressure metalorganic chemical vapor deposition (LP-MOCVD) on Si(111) with AlN buffer layer was studied using Convergent Beam Electron Diffraction (CBED). The 180 nm-thick AlN buffer was deposited at 900°C using TMAl and $NH_3$ as precursors, and was covered with 100 nm-thick $SiO_2$ in which 5 $\mu$m-wide stripes separated by 35 $\mu$m were exposed using standard photolithography and wet etching. LEO GaN stripes were obtained by performing a regrowth at ~1060°C using TMGa and $NH_3$. CBED patterns were obtained at 200 kV for the $< 1\bar{1}00 >$ zone axis. When indexing the diffraction pattern, the 180-degree inversion between image and diffraction pattern was considered. The experimental CBED patterns were taken from LEO GaN regions in which the threading dislocation density is less than $10^6 cm^{-2}$. Inversion domain boundaries were not found in both cross-section and plan-view samples by TEM. Simulations of the CBED patterns were done using the commercial software Desktop Microscopist 2.0. The simulated patterns were calculated by solution of the many-beam equation with 33 zero-order reflections. The LEO GaN on Si(111) was shown to be of Ga-face polarity, as is the case for GaN on sapphire grown by MOCVD. The consequences of the polarity for the morphological evolution of LEO GaN and the design of device structures are discussed.

**W3.4**
CRYSTALLOGRAPHIC TILTING IN THE LATERAL AND PENDEO EPITAXIAL OVERGROWTH OF GaN.
Okhyun Nam, Cheolsoo Sone, Ighyeon Kim, Yongjo Park, Taeil Kim, SAIT(Samsung Advanced Institute of Technology), Photonics Lab, Suwon, KOREA.

Lateral epitaxial overgrowth (LEO) technique has extensively been studied by many research groups, since NCSU and NEC first demonstrated the reduction of the dislocation density due to the lattice mismatch between GaN and substrate and Nichia chemical reported the increased life time of GaN based LDs on the laterally overgrown GaN (ELOG). However, the recent report showed that the arrays of dislocations are formed in the coalesced regions over the $SiO_2$ mask and these defects are closely related to the crystallographic tilting of the overgrown layers. This crystallographic tilting should be minimized to avoid the generation of dislocations and to fabricate the large area devices on the LEO GaN. In this paper, we report the effect of the growth parameters such as temperature and TMG flow rate on the crystallographic tilting of LEO GaN on sapphire substrates. Tilting angles measured by DCXRD were increased with the higher growth temperature and the lower TMG flow rate (> 1 degree). Pendeo epitaxy of GaN was also conducted and characterized by TEM and DCXRD. Two kinds of boundaries were observed in the pendeo epitaxy GaN. The tilting mechanism of the GaN grown laterally from the side wall of the seed GaN and the overgrown GaN on the mask is discussed in terms of surface interaction between the $SiO_2$ mask and LEO GaN.

**W3.5**
LATERAL EPITAXIAL OVERGROWTH VS. PENDEO-EPITAXY OF GaN STRUCTURES - A FINITE ELEMENT ANALYSIS.
Tsvetanka Zheleva, Waeil Ashmawi* and Kenneth A. Jones Sensors and Electron Devices Directorate, Army Research Laboratory, AMSRL-SE-EM, Adelphi, MD; *Department of Mechanical Engineering, North Carolina State University, Raleigh, NC.

Recent studies on selective growth of GaN structures via conventional lateral epitaxial overgrowth (LEO) and pendeo-epitaxy (PE) on 6H-SiC substrates, as well as sapphire substrates, unambiguously revealed that the regions of lateral growth exhibit four-to-five orders of magnitude lower density of dislocations compared to the regions of

vertical growth. The above phenomenon is successfully utilized in novel blue laser diodes with drastically improved life times. However, it is still not clear why and how the change of the growth direction of the selectively grown GaN from vertical to lateral in both LEO and PE enables this drastic reduction in the defect density. The most probable explanation is the free-standing lateral growth in pendeo-epitaxial GaN structures, as well as the quasi-free-standing lateral GaN growth during the conventional LEO process and the associated stress reduction . In both cases the crystallographic template (the matrix) for the lateral growth are the $\{11\bar{2}0\}$, $\{1\bar{1}00\}$, or the $\{1\bar{1}01\}$ side facets of the GaN. Analysis of the experimental data of time and temperature dependence of the propagation of the vertical and lateral GaN growth fronts, and examination of the morphology of the top surfaces, side facets, and interfaces of the LEO- and PE-GaN stripes with the underlying and adjacent interfaces, reveals their strong correlation with the diffusion related characteristics of the adatom species. It is also evident the strong correlation between the repeatedly observed in transmission electron microscope (TEM) morphologies of the side and top surfaces and interfaces and the thermally generated stress/strain gradient profiles as calculated via finite element analysis (FEA). A comparison between the stress distribution as a result of the mismatch in the coefficients of thermal expansion among the films in the structures, grouped in four types with different geometries will be presented: 1) conventional LEO-GaN; 2) conventional LEO-GaN case without $SiO_2$ layer; PE-GaN - mode A; and 4) PE-GaN - mode B. The range in stresses is least in the conventional LEO - GaN geometry with $SiO_2$ mask layer removed - from compressive of 2.6 GPa to tensile of 0.45 GPa, opposing to the maximum range of stresses in PE-GaN mode A geometry - from compressive of 3.8 GPa to tensile of 0.6 GPa. Stresses in all, but the conventional LEO-GaN geometry, are localized within the window/GaN column regions. The role of the (i) window width (LEO - case) or GaN column width (PE case); (ii) LEO/PE GaN stripe width; and (iii) the thickness of the LEO/PE GaN layer will be discussed in therms of tendencies for stress reduction.

**W3.6**
LOCAL STRAIN RELAXATION IN EPITAXIAL LATERALLY OVERGROWN GaN. Q.K.K. Liu, Bereich Theoretische Physik, Hahn-Meitner-Inst, Berlin, GERMANY; A. Hoffmann, A. Karschner, Inst fuer Festkoerperphysik, Technische Univ, Berlin, GERMANY; J. Christen, T. Rieman, F. Bertram, Inst fuer Experimentelle Physik, Otto-von-Guericke Univ, Magdeburg, GERMANY; K. Hiramatsu, Dept of Electrical and Electronic Engineering, Mie Univ, Mie, JAPAN.

Local strain relaxation as well as inhomogeneous impurity incorporation in epitaxial laterally overgrown (ELOG) structures is microscopically characterized using spectrally resolved scanning cathodoluminescence (CL) and micro-Raman spectroscopy. A correlation of the optical properties with local strain and free-carrier concentrations of ELOG structures oriented along the (1 = 120) and (1 = 100) directions is comprehensively studied. It is demonstrated that the structural properties change drastically going from the overgrown region to the coherently grown range. Furthermore, a comparison of the results between $SiO_2$ and W masks is given. To understand quantitatively the local strain relaxations of ELOG, we apply the continuum theory, simulated by the finite-element method. The influences of voids, interdiffusion of atoms from the mask, and impurity incorporation are parametrized. The effect of the different orientations of the mask is also examined. The resulting strains are compared with values deduced experimentally from CL microscopy and micro-Raman spectroscopy.

**W3.7**
THE EPITAXIAL LATERAL OVERGROWTH AND CHARACTERIZATION OF GaN PYRAMIDS. Xiuling Li, J.J. Coleman and Paul W. Bohn, University of Illinois, Urbana, IL.

We report on the growth, optical and structural characterization of epitaxial lateral overgrowth (ELO) of GaN starting from arrays of GaN pyramids. The growth was carried out in a vertical atmospheric pressure MOCVD reactor on a $SiO_2$ patterned sapphire substrate covered with a thin buffer layer of GaN. The original mask opening (either circles or hexagons) is 1- 6 $\mu$m with a center to center spacing of 8 $\mu$m. They are arranged in a stripe fashion (70 $\mu$m wide) bounded by a large area of $SiO_2$ on both sides. Under certain growth conditions, GaN pyramids form on such mask. Prolonged growth results in the elongation of the GaN pyramids in the $(11\bar{2}0)$ direction and then the corner-to-corner coalescence of the pyramids. Cathodoluminescence (CL) and near field scanning optical microscopy (NSOM) and spectroscopy are used to characterize the spatially resolved optical properties, particularly, the band-edge and the yellow emission. It is found that in the region where GaN was deposited homoepitaxially vertically on the coalesced GaN pyramids band-edge emission is remarkably intense. In addition, the band-edge emission is strongly blue-shifted in this region and strongly red-shifted on the elongated sidewalls. No yellow emission can be observed in the homoepitaxial region however, it is strong on the apex of the elongated pyramids. Defects, impurities and strain distribution in the ELO GaN pyramids will be analyzed based on the spatially resolved optical characterization, along with transmission electron microscopy (TEM) and SIMS studies of these structures.

**W3.8**
STRUCTURAL AND OPTICAL CHARACTERIZATION OF LATERALLY OVERGROWN GaN. R. Zhang, Y.G. Zhou, B. Shen, S.L. Gu, Y, Shi, Y.D. Zheng Laboratory of Solid State Microstructures and Department of Physics, Nanjing University, Nanjing, CHINA; L. Zhang, D.M. Hansen and T.F. Kuech, Department of Chemical Engineering, University of Wisconsin, Madison, WI.

Structural and optical properties of epitaxially laterally overgrown (ELO) GaN on patterned GaN 'substrate' by hydride vapor phase epitaxy (HVPE) have been investigated in this paper. The GaN 'substrate' is a pre- metalorganic vapor phase epitaxy grown GaN film on a (0001) sapphire substrate covered with a ~100nm thick patterned $SiO_2$ layer. The pattern consists of parallel stripes along $< 1 - 100 >$ directions exposed to the growth ambient with the period of 12 microns and the window of 4 microns. GaN are grown by HVPE using standard reaction source and carrier gases under the condition of Tg=1100°C, V/III=33, and mole fraction of $NH_3$, $[NH_3]$=0.0076. The epitaxially lateral overgrowth of GaN on $SiO_2$ areas is observed. After 1 hour growth, a planar ELO GaN film with the thickness of 10 microns is obtained. Microzone Raman scattering spectrometer, scanning electron microscope (SEM), transmission electron microscope (TEM) and atomic force microscope (AFM) are used to study the structure and surface morphology of the ELO GaN materials, while room-temperature cathodoluminescence (CL) and low-temperature photoluminescence (PL) are employed to explore the optical properties of the sample. Microzone Raman spectra taken in both the ELO and window areas clearly show E2 phonon scattering peak. AFM image indicate that the step termination is too little to be detected in a 2x2$\mu$m area in the ELO region. Low-temperature PL reveals that there are dominant bandedge emission line and a weak yellow band in the PL spectrum. CL measurements together with SEM observations imply that the yellow luminescence comes from the GaN window area. TEM observations show that the dislocation density is very low in the ELO region.

**W3.9**
HYDRIDE VAPOR PHASE EPITAXY (HVPE) OF GaN ON SELF-FACETTED SAPPHIRE SHAPED RIBBON CRYSTALS. V.A. Ivantsov, M.G. Minbaeva, A.I. Babanin, I.P. Nikitina, A.E. Nikolaev, V.M. Krimov, P.I. Antonov, Ioffe Institute, St. Petersburg, RUSSIA; I.S. Kotousova, Crystal Growth Research Center, St. Petersburg, RUSSIA.

Appropriate chemical and mechanical properties accompanied with commercial availability have been made sapphire one of the most popular substrate material for GaN epitaxy. Even a little change in mechanical preparation procedure of the substrates (including difference in treatment duration) may lead to unreproducible results of the epitaxy. To avoid any mechanical treatment, virgin surface of sapphire crystals is preferred to be used for GaN epitaxy. The proper technique to produce substrates having such surfaces is the Stepanov (EFG) self-facetted-ribbon growth method. In this work, substrates cut from 10 mm wide (0001) Stepanov as-grown ribbon sapphire crystals were used for subsequent HVPE growth of GaN without any buffer layer. Hot-wall horizontal rector was used to deposit 20 $\mu$m thick GaN layers simultaneously on the Stepanov (S) and referred commercial Union Carbide (UC) substrates. The AES and RHEED measurements were done to analyze elemental and structural composition of the substrate surface before and after chemical treatment prior the epitaxy. The XRD measurements performed in $\Omega$-scanning geometry at (0002) reflection were utilized to evaluate the structural perfection of the HVPE grown layers. The results showed that the FWHM of the XRD rocking curves from GaN epilayer grown on the S-substrate (cleaned from the surface contamination by chemical etching) is about 1.5 times narrower than that of on the UC-substrate (e.g., 434 arcsec and 628 arcsec, respectively). So, the use of the Stepanov self-facetted sapphire substrates improves the structural perfection of the GaN epitaxial layers. Rather surprising, this result was obtained on the S-substrate having growth steps with a height of 350-1400 $\AA$.

**W3.10**
THE GROWTH OF GaN EPILAYERS ON BULK-LIKE GaN SUBSTRATES. Yu.V. Zhilyaev, V.V. Belkov, E.E. Zavarin, B.V. Pushniy, S.D. Raevskiy, I.N. Safronov, A.S. Usikov, N.M. Shmidt, A.F. Ioffe Physico-Technical Institute, St. Petersburg, RUSSIA.

Results of GaN epitaxial growth on bulk-like GaN substrates are reported. At first,the GaN wafers were grown in the open tube chloride system Ga-HCl-$NH_3$-$H_2$, on sapphire (0001) and silicon (100)

and (111) substrates at 900° C. Special initial sapphire and silicon treatment allowed us to separate GaN layers from the substrates for following GaN growth. Then, n-GaN epilayers and p-n structures were grown by low pressure MOCVD on back side mirror - like surface of the GaN substrates. The possibility to reduce a density of nano and micropipes by several orders of magnitude using surfactantes and optimal thickness of buffer layer are shown. The results of the investigation of optical and electrical properties of single GaN epilayers and p-n junctions grown on the bulk-like FS-GaN substrates will be presented.

**W3.11**
ELECTRICAL AND LUMINESCENT PROPERTIES OF GaN CRYSTALS GROWN FROM LIQUID PHASE AT REDUCED PRESSURE. A.Y. Poyakov, A.V. Govorkov, N.B. Smirnov, M.G. Mil'vidskii, Institute of Rare Metals, Moscow, RUSSIA; V.A. Sukhoveev, V.A. Ivantsov, A.F. Ioffe Fiziko-Technical Institute RAS, St.-Petersburg, RUSSIA; V.A. Dmitriev, TDI, Inc. Gaithersburg, MD.

Crystals of GaN of about 20 mm in size were grown from liquid phase at reduced pressure (below 2 atm.) by seeded technique. X-ray analysis shows that the samples are textured with the preferred orientation of the c-axis in the vertical growth direction. The surface of the crystals bears evidence of the presence of Ga inclusions. The electron concentration in the crystals is on the order of $10^{19}$ $cm^{-2}$ with the electron mobility of about 30 $cm^2/V.s$. MCL spectra show a very pronounced yellow luminescence band and a weak near-bandedge luminescence at 3.35 eV (300K) and 3.425 eV (95K). Imaging the crystals in SEM in the secondary electrons mode does not reveal any features attributable to grain boundaries. MCL mapping of the samples in the near-bandedge shows the presence of mosaic nonuniformity. When mapped in the yellow luminescence band the image presents an agglomeration of dark spots with a bright halo. Such a contrast is explained by the regions of the grain boundaries producing higher yellow luminescence intensity.

**W3.12**
INTEGRATION OF PLZT FAMILY OXIDES WITH GaN. Andrei Osinsky, Vladimir Fuflyigin, Feiling Wang, Peter Vakhutinsky, Peter Norris, NZ Applied Technologies, Woburn, MA.

Combining ferroelectric oxide materials with III-nitride WBG semiconductors presents a special interest for high-speed image processing applications. High-speed, high density arrays of spatial light modulators (SLM) including high voltage GaN based circuitry, which is transparent in the visible and near UV range, can be built from these structures. We report for the first time, growth and characterization of electric and electro-optic properties of the high quality oxide films of PLZT family on n-GaN/C-$Al_2O_3$ structures. Single-phase 0.5-5 $\mu$m thick layers with compositions 0/52/48 and 9/65/35 were grown by sol-gel technique. Crystallinity and orientation of the oxide films were found to be dependent on the growth conditions as well as on presence of the nucleation buffer layer. Ferroelectric hysteresys loops, optical phase shift, I-V and C-V measurements were used to characterize the PLZT/GaN capacitors. Hysteresys loops were found to be either symmetrical or asymmetrical with respect to zero bias depending on the introduction of the thin oxide buffer prior PLZT growth. Values of Ps were in 25-40 $\mu C/cm^2$ range. The PLZT/GaN structures exhibit hysteretic electro-optic behavior typical for ferroelectrics. We measured a strong E-O effect with large field induces birefringence. The obtained $\sim\Delta n$ value was comparable with the best reported for films of the same composition grown on single crystal sapphire substrates.

**W3.13**
HVPE AND MOVPE GALLIUM NITRIDE GROWTH ON SLIGHTLY MISORIENTED SAPPHIRE SUBSTRATES. Olivier Parillaud, Volker Wagner, Hans-Jorg Buhlmann and Marc Ilegems, Institute of Micro- and Optoelectronics, Swiss Federal Institute of Technology, Lausanne, SWITZERLAND.

Due to the lack of suitable GaN substrates, (0001) exact $Al_2O_3$ is the principal substrate used for the realization of GaN-based devices. To our knowledge, very few reports concern the MOVPE of GaN on slightly misoriented $Al_2O_3$, and none deals with HVPE on such substrates. However, for other III/V compounds like GaAs or InP, it has been shown that the use of few degrees misoriented substrates could be very efficient to improve both crystal quality and surface morphology of the layers grown by HVPE. As a matter of fact, the supersaturation of the gas phase is quite small in the hydride technique as opposed to the MOVPE systems and growth occurs near the thermodynamic equilibrium as predicted by the Burton, Cabrera, and Frank theory. In this paper we present the gallium nitride growth both by the MOVPE and the HVPE techniques on C-axis sapphire with 2, 4 and 6 degrees disorientation around A or M directions. Surface morphology and growth rates are compared with those obtained on exact C-axis oriented sapphire, all the other parameters being kept constant. As expected, the steps already present on the substrate surface help to initiate a directed step-flow growth mode. The large hillocks which are typical for HVPE GaN layers on (0001) sapphire planes are replaced by more or less parallel macro-steps. The width and height of these steps, due to step bunching effect, depend directly on the disorientation angle and on the growth conditions and are clearly visible by optical or scanning electron microscopy. Atomic force microscopy and high-resolution XRD measurements have been carried out to quantify the surface roughness and crystal quality changes. Further optical and electrical characterization of the GaN layers is in progress.

**W3.14**
HYDRIDE VAPOUR PHASE HOMOEPITAXIAL GROWTH OF GaN ON MOVPE-GROWN TEMPLATES. T. Paskova, E.B. Svedberg, S. Tungasmita, IFM, Linköping University, Linköping, SWEDEN; R. Beccard, M. Heuken, Aixtron AG, Aachen, GERMANY; B. Arnaudov, S. Evtimova, Faculty of Physics, Sofia University, Sofia, BULGARIA; A. Henry and B. Monemar, IFM, Linköping University, Linköping, SWEDEN.

The significant lattice mismatch between GaN and the most commonly used sapphire substrates has required the development of multistep pre-growth processes involving either a sapphire nitridation or GaCl pretreatment, or using different buffer layers. It has been shown that the optimisation of nucleation steps can play a dominant role in determining the properties of subsequently grown layers. While recent results indicate great promise for the combination of metalorganic chemical vapour deposition (MOCVD)-grown GaN templates with subsequent homoepitaxially grown GaN by molecular beam epitaxy, only preliminary data have been presented on the use of MOVPE-GaN templates in hydride vapour phase epitaxial (HVPE) growth of thick GaN layers. We report on an improved quality of thick HVPE-GaN grown on MOCVD-GaN template layers compared to the material grown directly on sapphire. The GaN layers with a thickness in the range of 20-80$\mu$m were grown in a conventional HVPE system at growth temperature of 1090°C. The reference samples were grown using a nitridation pretreatment of the sapphire. The MOCVD-GaN template layers with a thickness of 2$\mu$m were grown in the Aixtron application laboratory. All samples grown on GaN template layers exhibit significantly smoother film surfaces and a reduction of the dislocation density. A change from mixed screw-edge character to a pure screw or pure edge type of dislocations has been revealed by both atomic force microscopy and transmission electron microscopy investigations. The film-substrate interface revealed by cathodoluminescence measurements shows an absence of highly doped columnar structures, which are typically present in thick HVPE-GaN films grown directly on sapphire, resulting in a reduction of two orders of magnitude of the free carrier concentration from Hall measurements. It was found that the structure, morphology, electrical and optical properties of homoepitaxial thick GaN layers grown by HVPE were strongly influenced by the growth rate. Details of these results will be presented.

**W3.15**
THE NATURE AND IMPACT OF ZnO BUFFER LAYERS ON THE INITIAL STAGES OF THE HYDRIDE VAPOR PHASE EPITAXY OF GaN. Shulin Gu, Jingxi Sun, and T.F. Kuech, Dept of Chemical Engineering, University of Wisconsin, Madison, WI.

The initial nucleation and growth of GaN on sapphire substrates can determine the materials properties of the subsequent epitaxial layer. In the case of the hydride vapor phase epitaxy process, this nucleation behavior can be improved by the inclusion of a ZnO intermediate or buffer layer. In many cases, the ZnO layer has been reported not to survive the initial heating and pre-growth treatment and is not reported to be present in the final epitaxial multi-layer structure. We have studied the formation, annealing and structure of ZnO layers when used to promote nucleation and improve the subsequent GaN growth. In particular, the structure and composition of the ZnO-sapphire interface after high temperature annealing was investigated by AFM, RHEED and XPS measurements. The ZnO layers were formed through reactive sputtering in a plasma-based system. The initially amorphous ZnO develops an epitaxial relationship to the underlying sapphire during the initial stages of the in situ pre-growth anneal but subsequently reactively dissociates under these HVPE pre-growth annealing conditions leaving a smooth surface. XPS measurements indicate, however, the formation of a thin residual Zn-containing layer on the sapphire surface. The structure and evolution of the initial GaN growth layer, typically 100nm thick, on these ZnO-derived surfaces was determined. The GaN structural properties were a function of the initial ZnO layer thickness under identical growth conditions. The impact of the GaN growth rate and gas phase stoichiometry on the structural and morphological properties of the GaN was determined in the context of the nature of this initial nucleation layer.

**W3.16**
VISIBLE AND IR EMISSION OF GaN:Er THIN FILMS GROWN BY SPUTTERING. Hong Chen, K.Gurumurugan and M.E. Kordesch, Department of Physics and Astronomy, Ohio University, Athens, OH; W.M. Jadwisienczak, H.J. Lozykowski, School of Electrical Engineering and Computer Science, and Condensed Matter and Surface Science Program, Ohio University, Athens, OH.

In this paper, we report the investigation of Er-doped GaN grown on sapphire and silicon substrates by sputtering with different doses of erbium. The films were characterized by X-ray diffration (XRD), optical transition (T%), Rutheford backscattering spectroscopy (RBS), cathodoluminescence (CL) and photoluminescence (PL) spectroscopy in the visible and infrared (IR) spectral region in wide range of temperature. XRD measurement indicate that as grown GaN:Er films deposited at high substrate temperature were policrystalline and retain structure even after annealing in $N_2$ ambient at 950° C. Recorded PL and CL spectra reviled the sharp characteristic emission lines corresponding to $Er^{3+}$ intra - $4f^n$ shell transitions over the temperature range of 8.5 - 300 K. Under above band gap excitation and electron excitation $^4S_{3/2}$ and $^4F_{9/2}$ transitions are dominating and superimpose on the broad 'yellow band'. The simplicity of applied spattering method for deposition of GaN thin films doped during growth with Er and obtained results indicate the suitability of that material for optical device applications

**W3.17**
GALLIUM NITRIDE IN A MESOPOROUS MATRIX OF MCM-41. Holger Winkler, Roland A. Fischer, Ruhr-Universitaet Bochum, Inst of Inorganic Chemistry, Bochum, GERMANY; Roland Schmechel, Heinz von Seggern, Technische Universitaet Darmstadt, Dept of Materials Science, Darmstadt, GERMANY.

The semiconducting group-III nitrides show great promise for electronic and optoelectronic devices. In the case of Gallium Nitride there are some unique properties like a wide and direct bandgap of 3.45 eV, low compressibility, high thermal conductivity, chemical inertness and radiation resistance. While the formation of thin films of GaN realized by MOCVD or MBE has been well established leading to quantum wells currently used in devices (bright blue LEDs and laser diodes), there is no satisfying chemical process available to produce quantum-confined GaN structures in less than two dimensions. Conventional lithographic or etching techniques are rather costly and connected with limited resolution. Besides there is excitonic quenching at etchdamaged boundaries. The mesoporous molecular sieve MCM-41 that consists of tunable hexagonally arranged uniform pores (2-10 nm in diameter) of hollow cylinders offers a possibility for synthesizing mesoscopic composites by inclusion chemistry. If homogeneously filled with GaN, a GaN@MCM-41-composit would result in an ordered array of uniform quantum wires/ dots in the molecular sieve matrix. We describe the organization of nanodispersed GaN in MCM-41 of 2.7 nm pore diameter via impregnation with a solution of the single-source precursor triazido(trimethylamin)-gallium in toluene. TEM investigations showing the well ordered porous system of MCM-41 still being intact after the loading with Gallium Nitride (Ga-content about 10 wt.-%, molar ratio Ga : N = 0.7 to 1.1). The decrease of the BET surface area of the composites GaN@MCM-41 of about 75% in comparison of that of pure MCM-41 material give a strong hint for porefilling, which is emphasized by the overall lowered intensity of the low-angle XRD pattern of the composites. In addition optical investigations (photoluminescence and excitation spectroscopy) showing a green luminescence and a blue-shifted bandgap of about 3.7 eV indicate nanodispersed Gallium Nitride to be present inside the pores of MCM-41.

**W3.18**
GROWTH KINETICS OF GaN THIN FILMS GROWN BY MOVPE USING SINGLE SOURCE PRECURSORS. Roland A. Fischer, Anjana Devi, Wolfram Rogge, Andreas Wohlfart, Anorganische Chemie II, Ruhr Universitaet Bochum, GERMANY.

We report the epitaxial growth and characterization of GaN thin films using the single source precursor bisazidodimethylaminopropyl gallium (BAZIGA) in a cold wall reactor. Transparent, smooth, epitaxial (FWHM 0.036°) and stoichiometric GaN films were grown on sapphire substrates in the temperature range 870 - 1320K and high growth rates were obtained (3-10$\mu$/hr). Film growth was studied as a function of substrate temperature as well as reactor pressure. Although high quality films were obtained without using any additional source of nitrogen such as ammonia, we have investigated the influence of ammonia on the growth and properties of the resulting films. The films obtained were characterized by XRD, AFM, SEM, AES and the PL spectroscopy (at 300K) of GaN films grown exhibited the correct near band edge luminescence at 3.45 eV. A study on the fragmentation of the precursor molecule in the boundary layer was undertaken to analyze the concentration of the fragments such as $HGaN_x$ and $GaN_x$ in the boundary layer as a function of temperature to correlate with the growth rate by molecular beam sampling via pin hole, MS and REMPI-TOF spectroscopy.

**W3.19**
SUPPRESSION OF GAS PHASE ADDUCT REACTIONS IN THE MOVPE OF GaN. A. Thon, 3T-True Temperature Technologies, Misgav, ISRAEL; Nicole Pauly and T.F. Kuech, Department of Chemical Engineering, University of Wisconsin, Madison, WI.

Trimethyl gallium-trimethyl amine (TMG:TMN) adduct formation and decomposition as alternative cation precursor for MOVPE of GaN was studied by means of in-situ mass spectroscopy in an isothermal flow tube reactor. The temperature, pressure and reaction time were chosen to emulate the gas phase environment typical of the metal-organic vapor phase epitaxy (MOVPE) of GaN. Dynamic changes in the mass spectra are reported for the gas phase reactions between trimethyl gallium (TMG) and TMN in hydrogen ($H_2$ or $D_2$ ) and ammonia ($NH_3$ or $ND_3$ ) ambient. The decomposition of TMG/TMN exhibits a cooperative decomposition. Decomposition of TMN above 500°C is enhanced relative to thermal homolysis, probably due to interaction between TMN and decomposition products of TMG. In the case of TMG/ammonia based growth, methane evolution at low temperatures and the subsequent oligimerization of the adduct-derived reaction products are key features of conventional MOVPE Growth. The formation of higher molecular weight products, due to this oligimerization, complicates the growth behavior of the GaN and could impact the materials properties. Unlike the extremely fast reaction between TMG and ammonia, the presence of TMN within the system appears to completely suppress the gas phase reaction for temperatures less than ~500°C. No methane, derived from the intramolecular reaction of the TMG/ammonia adduct, is observed over a broad temperature range. The implications of this unexpected finding on the reactor design and chemistry will be discussed.

**W3.20**
GAS PHASE CHEMISTRY AND MATERIAL PROPERTIES DURING METALORGANIC VAPOR PHASE EPITAXY OF GaN. Jingxi Sun, J.M. Redwing*, T.F. Kuech, Department of Chemical Engineering, University of Wisconsin-Madison, Madison, WI; *Epitronics, Phoenix, AZ.

GaN-based devices have been fabricated successfully using the metalorganic vapor phase epitaxy (MOVPE) technique, however, many fundamental growth-related problems remain unresolved. The metal-organic vapor phase growth of GaN is complicated by the extensive and pervasive complex gas phase chemistry within the growth system. This gas phase chemistry leads to the high sensitivity of the material properties on the detailed fluid dynamics within the system. In this study, the gas phase chemistry of TMG-NH3 based growth system and its effect on material properties were investigated in an effort to develop general engineering guidelines for growth and reactor design as well as further understanding of growth chemistry. The transport behavior was studied initially using computational fluid dynamics (CFD) based modeling, and several features associated with growth of device quality materials were discovered. A thin high temperature flow of 1.0 - 2.0 cm is formed above the growth front. Through the combination of reactor modeling and gas phase kinetic studies, we have identified a stratified gas phase chemical structure within this thin high temperature flow that leads to such process complexities. A chemically stratified gas phase structure is formed inside the high temperature flow sheet above the growth front in which there is a region containing predominantly high molecular weight species above region characterized by low molecular weight product. This stratified chemical structure is attributed to the high growth temperature and high thermal gradient resulting from high flow rate as well as the presence of high molecular weight species due to oligimerization of the adduct-derived species. This layered structure is closely related to the transport and reaction behavior inside GaN MOVPE processes, which can serve as an engineering guideline for GaN MOVPE growth and reactor design. Since the very high temperature near the growth front leads to the decomposition or fragmentation of the reaction products into low molecular weight moieties which control the growth rate, growth models of different complexity can produce similar growth rate predictions that are consistent with experimental data. We have combined these numerical results with detailed experimental measurements within the modeled system. We designed a novel multiannular gas inlet for a working horizontal reactor, which allows continuous tunability of the mixing and residence time of two precursors. The detailed gas phase behavior and its effect on material properties, as well as the implications of these findings for the design of GaN systems and material performance, will be presented.

**W3.21**
GROWTH OF HIGHLY ORIENTED HEXAGONAL GALLIUM NITRIDE FILMS BY MOCVD USING NOVEL SINGLE

PRECURSORS. Young Kuk Lee, Chang Gyoun Kim, Myung Mo Sung, Sun Sok Lee, Sung Yong Lee, Seung Ho Yu, Sang Heon Lee, Ju Ho Lee, and Yunsoo Kim, Korea Research Institute of Chemical Technology, Advanced Materials Div, Taejon, KOREA.

Volatile single precursors were synthesized by the reaction of trialkylgalliums with alkylhydrazine hydrogen chloride adducts ($H_2NNHCH_3 \cdot HCl$) followed by the reaction with $NaN_3$. Novel dialkylazidogallium hydrazide adducts were obtained as liquids or volatile solids depending on the alkyl groups of the gallium metal. The physical properties of the precursors showed they were reasonably suitable as single precursors for MOCVD. These precursors with large N/Ga ratios might overcome the nitrogen deficiency commonly observed in the GaN films produced by metal organic chemical vapor deposition (MOCVD). They were employed in the deposition of GaN films on Si substrates in the temperature range 500∼800°C by MOCVD. The deposited $h$-GaN films were characterized by X-ray photoelectron spectroscopy (XPS), X-ray diffraction (XRD), double crystal X-ray diffraction (DCXD), X-ray pole figure, scanning electron microscopy (SEM) and photoluminescence (PL) spectroscopy. The XRD results have shown that the films grew with the highly preferred orientation of [0001] direction without any rhombic or prismatic faces. Other structural properties such as surface morphology, full-width at half maximum (FWHM) of the GaN (0002) reflection, and pole figure of the GaN films grown in this experiment will be discussed. The photoluminescence spectra of the films will also be discussed for the optical application.

**W3.22**
PRECURSOR REACTIONS IN NITRIDE CVD. Michael E. Bartram, J. Randall Creighton, Jung Han, Jeffery J. Figiel and Thomas M. Kerley, Sandia National Laboratories, Albuquerque, NM.

Depletion effects and particle formation in CVD processes are often attributed to reactions between precursors in the gas-phase prior to deposition. Few detailed studies of these reactions have been carried out under CVD conditions however, often forcing modeling efforts to draw upon reactions observed in condensed phases. We have examined the interactions between a number of precursors in the gas phase using infrared spectroscopy (FTIR) and mass spectroscopy and by monitoring pressure changes which occur upon mixing. Our results provide no evidence for a reaction occurring between bis-dicyclopentadienyl magnesium (MgCp2) and ammonia and water from room temperature to 50 deg. C. MgCp2 also does not react with trimethylaluminum. This suggests that the formation of solids associated with MgCp2 may be due to cooling and pressure gradient effects in the reactor inlet. The reactions between NH3 and TMA and trimethylgallium (TMG) were measured as a function of temperature. Mass spectra of both the TMA:NH3 and the TMG:NH3 adducts were observed. However, evidence for these species decomposing to aminoalanes and aminogallanes in the gas phase was not obtained. In addition, results of FTIR studies of these reactions at high flow rates and high temperatures will be presented. (Sandia is operated by Sandia Corporation, a Lockheed Martin Company, for the USDOE under DE-AC04-94AL85000.)

**W3.23**
GROWTH AND CHARACTERISATION OF GaN LAYERS ON Si(111) SUBSTRATES. A. Strittmatter, D. Bimberg, Technische Universitat Berlin, Inst. f. Festkorperphysik, Berlin, GERMANY; A. Krost, J. Blasing, P. Veit. J. Christen, Otto-von-Guericke Universitat Magdeburg, Inst. f. Experimentelle Physik, Magdeburg, GERMANY.

GaN layers were grown onto Si(111) substrates by low-pressure metalorganic vapor phase deposition. The layers have smooth surfaces (rms roughness: <2 nm), strong excitonic luminescence (FWHM: 13 meV at 7 K), and narrow X-ray rocking curves of the GaN(0002) reflection (FWHM: 610 arcsec). This high quality was obtained by the introduction of an AlN/AlAs composite buffer layer before the main GaN layer was grown. We studied the quality of the main GaN layer in dependence of the AlN growth parameters (temperature, thickness, total pressure, ammonia flow). It turned out, that the total pressure during the deposition of the AlN layer on top of the AlAs layer strongly influenced the quality of the finally grown GaN layer. The higher the total pressure the narrower was the FWHM of the GaN(0002) rocking curve. The simple explanation, that the simultaneously increased partial pressure of ammonia was responsible for the structural improvement was not confirmed by the fact, that the ammonia flow had to be reduced from 1 slm to 0.25 slm at a total pressure of 800 mbar in order to obtain smooth GaN layers. However, q-2q x-ray diffraction scans revealed a structural transition of the underlying AlAs layer during the deposition of the AlN layer. If the total pressure during the AlN growth was below 200 mbar then the AlAs(111) reflection is clearly seen in the X-ray spectra independent of the growth parameters of the subsequent GaN growth. In contrast, if the total pressure was equal or above 200 mbar during the AlN growth, the intensity of the AlAs(111) reflection in the x-ray spectra was strongly reduced or even vanished while new reflections emerged with Bragg peak positions between the AlAs(111) and AlN(111) reflections. In order to get more insight into this interesting structural transition, such transformed layers are currently studied by transmission electron microcopy.

**W3.24**
GROWTH AND CHARACTERIZATION OF GaN THIN FILMS ON Si(111) SUBSTRATES USING SiC INTERMEDIATE LAYER. K.J. Lee, C.I. Park, K.C. Kim, S.C. Choi, W.-H. Lee, E.-K. Suh, G.M. Yang, and K.Y. Lim, Dept. of Semiconductor Science and Technology, Semiconductor Physics Research Center, Chonbuk National University, Chonju, KOREA; K.S. Nahm, Dept. of Chemical Engineering, Semiconductor Physics Research Center, Chonbuk National University, Chonju, KOREA.

SiC wafer offers a much smaller lattice mismatch to GaN than commonly used sapphire. However, the limited availability, such as the high cost and small size, represent significant practical obstacles to the use of 6H-SiC as substrates for GaN growth. We have demonstrated the ability to grow GaN films on Si wafers using SiC intermediate layer. GaN films have been grown atop Si- and C-terminated SiC intermediate layers on Si(111) substrates using low pressure metalorganic chemical vapor deposition (LP-MOCVD). The SiC intermediate layer was grown by chemical vapor deposition (CVD) using tetramethylsilane (TMS) as the single source precursor. The Si terminated SiC surface was obtained by immediately flow of SiH4 gas after growth of SiC film. LP-MOCVD growth of GaN on the SiC/Si(111) was carried out with trimethylgallium (TMG) and NH3. Single crystalline hexagonal GaN layers can be grown on Si terminated SiC intermediate layer using an AlN or GaN nucleation layer. Compared with GaN layers grown using a GaN nucleation layer, the crystal qualities of GaN films with AlN nucleation layer are extremely improved. The GaN films were characterized by x-ray diffraction (XRD), photoluminescence (PL) and scanning electron microscopy (SEM). Full width at half maximum (FWHM) of double crystal x-ray diffraction (DCXD) rocking curve for GaN (0002) on SiC/Si(111) was 890 arcsec. PL near band edge peak position at room temperature and FWHM are 3.37 eV and 79.35 meV, respectively. The yellow luminescence does not appear.

**W3.25**
INFLUENCE OF THE BUFFER LAYER COMPOSITION ON STRUCTURE AND OPTICAL PROPERTIES OF GaN THIN FILMS ON SILICON SUBSTRATE. Igor Berishev, Esther Kim, David Starikov, and Abdelhak Bensaoula, Nitride Materilas Laboratory, SVEC, University of Houston, Houston, TX; Irene Rusakova, Texas Center of Superconductivity, University of Houston, Houston, TX.

The epitaxial growth of GaN on Si is of particular interest to future high power, high frequency electronic and sort wavelength optoelectronic devices. The influence of the initial nucleation, buffer layer composition and growth modes is critical for the final layer properties, but is not yet fully understood. In our studies, the 2-3 $\mu$m thick GaN films and InGaN/GaN quantum well structures have been grown by RF plasma source molecular beam epitaxy on Si (111) wafers. Various buffer layers (AlN, SiN, GaN, and others) have been utilized in order to accommodate 17% lattice mismatch between GaN and Si. Resulting films were studied by transmission electron microscopy, X-ray diffraction, photoluminescence, and SIMS. All used buffer layers resulted in single crystal GaN films as evident from streaky two-dimensional RHEED and TEM electron diffraction patterns. However, we found a significant difference in width of x-ray diffraction spectra, high resolution and conventional TEM images, and PL properties. The best films had AlN buffer and demonstrated room temperature PL FWHM of 8.7 nm. These films also did not show radial deviations of crystal planes near buffer layer and were least defective as observed from TEM. Our SIMS studies have shown that interdiffusion of Ga(Al) and Si takes place and is shifted towards the substrate. We also studied and will present our data on influence of the buffer layers on the PL properties of InGaN QW structures grown on top of 3$\mu$m thick GaN layers.

**W3.26**
OPTICAL PROPERTIES OF MANGANESE DOPED AMORPHOUS AND CRYSTALLINE ALUMINUM NITRIDE FILMS.
Meghan L. Caldwell, Ronald C. Tucceri, Hugh H. Richardson, Ohio University, Dept of Chemistry and Biochemistry, Athens, OH; Wojciech M. Jadwisienczak, Henryk J. Lozykowski, Ohio University, Dept of Computer Science and Electrical Engineering, Athens, OH.

An aluminum nitride (AlN) film deposited on silicon (100) was used as the substrate for growing manganese (Mn) doped AlN film by metal organic chemical vapor deposition (MOVCD). The (6.11$\mu$) under layer of AlN was grown at 615°C at a pressure of $10^{-4}$ Torr. The (6.03$\mu$) top layer of Mn-AlN was grown at the same temperature

and pressure but doped with pulse valve introduction of the manganese (100 ms on, 100 ms off). The film was then characterized *ex situ* with IR reflectance microscopy, X-ray diffraction, scanning electron microscopy imaging, cathodoluminescence, X-ray fluorescence, Rutherford backscattering, sceondary ion mass spectrometry, photoluminescence, and atomic force microscopy. The IR reflectance measurements showed a strong ($A_1$) LO mode for AlN at 906 $cm^{-1}$ with a shoulder at 928 $cm^{-1}$. X-ray diffraction yielded three diffraction peaks at a 2Θ position of 33, 36, and 38 degrees corresponding to 100, 002, and 101 lattice planes respectively. Cathodoluminescence and photoluminescence results show strong visible emitted light from incorporated manganese. The relative percentage of manganese to aluminum was below the detection limit (0.2%) of the X-ray fluorescence spectrometer. Amorphous AlN doped Mn films have also been grown using a low temperature atomically abrupt sputter epitaxial system. The amorphous and crystalline Mn doped AlN luminescence properties will be compared and contrasted.

**W3.27**

A STUDY OF THE EFFECT OF V/III FLUX RATIO AND SUBSTRATE TEMPERATURE ON THE In INCORPORATION EFFICIENCY IN $In_xGa_{1-x}N$/GaN HETEROSTRUCTURES GROWN BY RF PLASMA-ASSISTED MOLECULAR BEAM EPITAXY. M.L. O'Steen, F. Fedler, R.J. Hauenstein, Oklahoma State Univ, Dept of Physics, Stillwater, OK.

Reflection High Energy Electron Diffraction (RHEED) and laterally spatially resolved High Resolution X-ray Diffraction (HRXRD) have been used to study the effects of the V/III flux ratio and substrate temperature on In incorporation during growth of $In_xGa_{1-x}N$/GaN heterostructures by plasma-assisted molecular beam epitaxy. The average alloy composition of the $In_xGa_{1-x}N$/GaN superlattices has been observed to be strongly affected by both the substrate temperature and the V/III flux ratio during growth. More than an order-of-magnitude decrease in the average alloy composition is observed in the temperature range 590–670° for a fixed V/III flux ratios. Additionally, the V/III flux ratio is observed to strongly affect the incorporation of In for samples grown at high temperatures, with an order-of-magnitude increase in incorporated In for only a slight increase in V/III flux ratio. RHEED patterns are presented which suggest identifciation of the processes leading to the reduction of incorporated In as surface-segregation and -desorption. Implications of this work for controlling In segregation and desorption in the growth of devices will be presented.

**W3.28**

DEPENDENCE OF IMPURITIES INCORPORATION ON POLAR DIRECTION OF GaN GROWTH ON C-PLANE SAPPHIRE. M. Sumiya, Y.J. Zhao[1], K. Yoshimura, K. Ohtsuka[2] and S. Fuke Department of Electrical and Electronic Engineering, Shizuoka University, Johoku Hamamatsu, JAPAN; [1]Department of Physics and Astronomy, Northwestern University, Evanston, IL, [2]Research and Development Division, Sanken Electric Co., Ltd., Kitano Niiza, JAPAN.

We have investigated the polarity of GaN films by coaxial impact-collision ion scattering spectroscopy (CAICISS). It was verified that the polar direction of GaN growth could be controlled by the polarity of an interface at GaN epi-layer growth [1]. In this study, we report that the more impurities including a p-type dopant are incorporated in N-faced GaN (-c polarity) films and that the polarity is critical not only to the grwoth mode but also to the properties of GaN films. Prior to the experiments, we predicted theoretically which polarity (+c or -c) of GaN would contain more impurities using ab initio molecular dynamics. GaN films with 1.2$\mu$m of thickness were deposited on c-plane sapphire substrates with and without the nitridation by an atmospheric two-step MOCVD method. Zn-doped GaN films were also deposited simultaneously on both HVPE (+c)- and MBE (-c)-GaN substrates by hot-wall epitaxy method. Both positive and negative ion impurities in GaN films were analyzed by secondary ion mass spectroscopy (SIMS). We calculated the adsorption energy of Ga, Mg and Zn on the nitrogen-terminated surfaces with +c and -c polarity. This calculation predicted that more p-dopants were incorporated into -c GaN due to the difference of adsorption energy between Ga and p-dopants. The photoluminescence related to Zn was observed only for -c GaN film (on MBE GaN). SIMS analysis reveals that Zn dopant was incorporated more into -c GaN as we predicted. For non-doped MOCVD-GaN films, the oxygen was detected more by two magnitude in -c GaN as Hellman et.al. reported [2]. Furthermore, the carbon, which probably came from TMG source gas, existed at higher level by one magnitude in -c GaN. Higher n-type carrier density in -c GaN film could be explained by the concentrations of these impurities. Thus, the polar direction of GaN growth is important to the incorporation of impurities, which should influence the properties of GaN films. [1] M. Sumiya et.al.; to be published in 08/02/99 issue of Appl. Phys. Lett. [2] E.S. Hellman et.al.; MRS internet J. Nitride Semicond. Res. Vol.1, 16 (1996)

**W3.29**

SURFACE MORPHOLOGY OF GaN: FLAT VERSUS VICINAL SURFACES. M.H. Xie, S.M. Seutter, L.X. Zheng, S.H. Cheung, Y.F. Ng, H.S. Wu, S.Y. Tong, The Univ of Hong Kong, Dept of Physics, HONG KONG.

The wurtzite structure of GaN films leads to special surface morphologies caused by strong anisotropy of growth. It shows triangular-shaped islands under the 2D nucleation growth mode and alternating smooth-rough step edges under the step-flow growth mode. The growth anisotropy is understood by considering the bonding characteristics of edge atoms. On a GaN(0001) surface, two types of steps are present, namely type-A and type-B steps. For a type-A step, each edge atom has two dangling bonds, whereas for a type-B edge, it has one dangling bond. This leads to a difference in the attachment rates of adatoms, thus an anisotropy in the growth rate between the two steps. A type-A step grows faster and has a rough front, whereas a type-B step advances slowly and has a smooth front. The ABABA... stacking sequence of a wurtzite film implies that type-A and type-B steps alternate along a given crystallographic direction, e.g., $[1\bar{1}00]$. Therefore, the fast-growing type-A step will catch up on the slow-growing type-B step and double bilayer steps will form. Comparing flat and vicinal surfaces, there are significant differences in their morphologies. The surfaces of GaN films grown on flat substrates are usually decorated by mounds caused by growth spirals at screw dislocations. In contrast, vicinally grown GaN films have very smooth surfaces, with evenly spaced steps to make up the misorientation. No mound is seen on vicinal surfaces. This result suggests an effective suppression of screw dislocations during GaN heteroepitaxy on vicinal SiC, the substrate used in this experiment. Finally, a step bunching phenomenon is observed on the vicinal surface. This is attributed to an electromigration effect, as the bunching depends on the direction of the direct current applied to heat the sample. By studying the dynamics of step bunching, we deduced the dominating kinetic processes of GaN growth.

**W3.30**

GROWTH OF InN BY MBE. Wei-Li Chen, Robert L. Gunshor, Jung Han, Koichi Higashimine, Nobuo Otsuka, Purdue University, West Lafayette, IN.

A series of experiments were performed to explore the growth of InN by MBE. An RF-plasma source was used to supply active nitrogen. MOCVD grown GaN epilayers (2-2.5 $\mu$m thick) on sapphire were used for the hetroepitaxy of InN. The nitrogen flux was estimated at 3.7x10^(14) atoms/$cm^2$/sec (0.33ml/sec for GaN) using RHEED oscillation during the growth of GaN (in the N-limited growth region), while the In flux ranged from 0.2ml/sec to 0.025ml/sec. The high anion-to-cation flux ratios were necessary to avoid In condensation. Thermodynamic and kinetic analysis for the challenges in avoiding In droplet will be discussed. In a study of InN dissociation, as measured by quadropole mass analyzer (QMA), it was observed that the dissociation of InN in vacuum was significant at temperatures below the previously-reported values. Growth temperatures for InN were chosen based on the result of the dissociation experiment. Periodic growth interruption was found effective in preventing the occurrence of In droplets. RHEED was used to monitor the surface evolution during the growth experiments. Depending on the source fluxes and substrate temperature, the RHEED in $< 11\bar{2}0 >$ direction during growth can be spotty, streaky with 2-fold reconstruction, or show the coexistence of both streaks and spots. It was found that growth under a 3-D spotty RHEED pattern generally leads to better film quality as judged by the optical absorption characteristics. An X-ray diffraction FWHM (rocking curve with (0002) diffraction) of 1100 arc-second was observed for an InN epilayer of around 0.25 $\mu$m thick. Further characterization of the grain structure was provided by AFM, and TEM.

**W3.31**

EVIDENCE FROM EELS OF OXYGEN IN THE BUFFER LAYER OF A MBE GROWN III-N HEMT. Tyler J. Eustis, Cornell University, Department of Materials Science and Engineering, Ithaca, NY; John Silcox, Cornell University, School of Applied Engineering Physics, Ithaca, NY; Michael J. Murphy, William J. Schaff, Cornell University, School of Electrical Engineering, Ithaca, NY.

The presence of oxygen throughout the nominally AlN buffer layer of a RF assisted MBE grown III-N HEMT was revealed upon examination by Electron Energy Loss Spectroscopy (EELS) in a Scanning Transmission Electron Microscope (STEM). The buffer layer is responsible for obtaining the polarity (gallium face) required for producing a piezoelectric induced high mobility two dimensional electron gas at the AlGaN/GaN heterojunction. Only AlN or AlGaN buffer layers have provided gallium face polarity in RF assisted MBE grown III-N's. The sample was grown at Cornell University in a Varian GenII MBE using an EPI Uni-Bulb nitrogen plasma source.

The buffer layer was examined in the Cornell University STEM using Annular Dark Field (ADF) imaging and Parallel Electron Energy Loss Spectroscopy (PEELS). PEELS of the nitrogen and oxygen K-edges at 5 Angstrom steps across the GaN/AlN/sapphire interfaces reveals the presence of oxygen in the AlN buffer layer. The ratio of oxygen to nitrogen in this 150 Angstrom buffer layer is a maximum of approximately 1 at the buffer/sapphire interface. The ratio then decreases over the thickness of the buffer layer and reaches zero at the GaN/buffer layer interface. It is unclear why the oxygen ratio reaches zero at the GaN. However, the gradient suggests the oxygen has diffused into the buffer region from the sapphire substrate forming this AlON layer. Bright Field TEM reveals a crystallographically sharp interface, while the PEELS reveal a chemically diffuse interface.

**W3.32**
HIGH TEMPERATURE LIMITATIONS OF GaN GROWTH BY RF-PLASMA ASSISTED MOLECULAR BEAM EPITAXY DUE TO ACTIVE NITROGEN SPECIES. T.H. Myers, A.J. Ptak, West Virginia University, Department of Physics, Morgantown, WV.

Growth of GaN by molecular beam epitaxy (MBE) is typically limited to temperatures less than 750°C due to increased desorption of Ga from the growing surface, resulting in a greatly reduced growth rate. The onset temperature of this decreased growth rate varies from group to group, and is typically lower than expected based on thermal decomposition rates for GaN. We will report on the relative reactivity of the various active nitrogen species produced by rf plasma sources: low and high energy ions, atoms and metastables. Reactivity is determined based on low temperature (~400°C) nitridation rates for sapphire. Studies of growth rate as a function of temperature suggest the GaN surface is prone to attack by neutral and ionic atomic nitrogen above 700°C, promoting decomposition. This leads directly to the observed lower than expected temperature for a significant decrease in growth rate, while this decrease is not observed when the active nitrogen flux consists primarily of nitrogen metastables. Growth kinetics for both (0001) and (0001) GaN surfaces will be discussed. This work was supported by ONR Grant N00014-96-1-1008 and monitored by Colin E. C. Wood.

**W3.33**
FORMATION OF BN AND AlBN DURING NITRIDATION OF SAPPHIRE USING RF PLASMA NITROGEN SOURCES. A.J. Ptak and T.H. Myers, Department of Physics, West Virginia University, Morgantown, WV; K.S. Ziemer and C.D. Stinespring, Department of Chemical Engineering, West Virginia University, Morgantown, WV.

Nitridation of the sapphire substrate prior to buffer layer growth continues to play an important role in molecular beam epitaxy (MBE) growth of the group-III nitrides. We present results that indicate B is generated during operation of at least two rf plasma sources, the Oxford Applied Research CARS-25 and EPI Vacuum Products, Inc. Unibulb. While the B can be at a relatively low level during nitride layer growth, Auger and XPS measurement of the time evolution of the nitridation layer indicate significant B incorporation occurs during nitridation. For some conditions, it appears that the formation of BN is likely. Reflection high energy electron diffraction measurements made during nitridation yield a time dependent lattice constant variation that can be interpreted as due to the formation of AlBN. A model that may explain one origin of the formation of cubic inclusions in MBE bufer layers will be presented. This work was supported by ONR Grant N00014-96-1-1008 and monitored by Colin E. C. Wood.

**W3.34**
THE EFFECT OF THE BUFFER LAYER ON THE STRUCTURE, MOBILITY AND PHOTOLUMINESCENCE OF MBE GROWN GaN. Nikhil Sharma, David Tricker, Vicki Keast, Department of Materials Science and Metallurgy, University of Cambridge, Cambridge, UK; Stewart Hooper, Jon Heffernan, Jenny Barnes, Alistair Kean, Sharp Laboratories of Europe, Oxford Science Park, Oxford, UK; Colin Humphreys, Department of Materials Science and Metallurgy, University of Cambridge, Cambridge, UK.

Although GaN has been grown mainly by metal organic chemical vapor deposition (MOCVD), molecular beam epitaxy (MBE) offers the advantages of lower growth temperatures and a more flexible control over doping elements and their concentrations. We are growing GaN by MBE on sapphire substrates, using a polycrystalline GaN buffer layer to reduce the misfit strain, thus improving the structural quality of the epilayer. The quality of the GaN epilayers (in terms of their photoluminescence, mobility and structure) has been investigated as a function of the buffer layer thickness and annealing time. The investigation showed that the mobility of the material was improved by increasing the buffer layer thickness and annealing time. This also had the effect of decreasing the defect density in the GaN epilayer, suggesting that the mobility improves with the structural quality of the semiconductor. Optical characterisation showed that the ratio of the donor band exciton (DBE) peak (3.47eV) to the structural peak (3.27eV) in the photoluminescence spectrum, measured at 10K, increased with decreasing defect density. The unwanted structural peak can be considered to originate from a shallow donor to a shallow acceptor transition, which is clearly related to the structural defects in GaN. Thus by increasing the buffer layer thickness and annealing time the structural quality, mobility and photoluminescence improves in the GaN epilayers. Structural characterisation by transmission electron microscopy (TEM) showed that the observed decrease in the DBE to structural peak ratio in the photoluminescence spectra could be correlated with an increase in the density of stacking faults in the GaN epilayers. The detailed structure of these stacking faults is being investigated by dark field and high resoloution TEM. Their effect on the electrical and optical behaviour of GaN is being assessed by determining the local change in the dielectric function in the vicinity of individual stacking faults. This is achieved by obtaining the low loss region (<50eV) of the electron energy loss spectrum using a scanning transmission electron microscope with a high spatial and energy resolution. The real and imaginary parts of the dielectric function can be extracted from the single scattering distribution of the low loss spectra by using the Kramers-Kronig relations.

**W3.35**
MBE GROWTH OF GaN FILMS IN PRESENCE OF SURFACTANTS: THE EFFECT OF Mg AND Si. Guido Mula, INFM and Dipartimento di Fisica, Univ. Cagliari, Cagliari, ITALY; C. Adelmann, B. Daudin, CEA/Grenoble, DRFMC/SP2M, Grenoble, FRANCE; P. Peyla, Univ. J. Fourier, Lab. de Physique et Modelisation des Milieux Condenses, Grenoble, FRANCE.

The understanding of the kinetics of the growing species on the GaN surface is of the foremost interest for optimum epitaxial growth. We present here results on the effect of the presence of Mg and Si on the growing surface of GaN. These materials, commonly used as dopants, have a strong influence on the kinetics of Ga and N atoms. The samples are studied by Reflection High Energy Electron Diffraction, Photoluminescence and Optical Microscopy. The effects on both cubic (c-GaN) and hexagonal (h-GaN) phases are presented. The growth rates and the final samples morphologies are significantly affected by the presence of dopants for dopant fluxes which are orders of magnitude lower than the Ga flux. The changes in the growth rates can be as high as 20% for a dopant flux of about 1/1000th of the Ga flux. A deep hollow in the growth rate of h-GaN is observed in presence of Mg as a function of the Ga flux. This has been attributed to a sudden formation of Ga droplets above a critical Ga flux due to the Mg-induced modification of the Ga surface mobility. A simple nucleation model is proposed, to account for the hollow observed in the case of h-GaN growth rate, that confirms the very abrupt onset of Ga droplet formation as a function of the Ga flux in presence of Mg. This fact is also confirmed by optical microscopy measurements on two samples, 1 micron thick, with and without Mg. A different behavior is observed in presence of Si atoms. We observed a strong modification of the sticking coefficient of N in the Ga-rich region, while there is no noticeable effect in the N-rich regime.

**W3.36**
SURFACTANT EFFECT OF Al IN PLASMA-ASSISTED MBE GROWN GaN. O. Zsebök, J.V. Thordson, Q.X. Zhao, U. Södervall, G. Swenson and T.G. Andersson, Department of Microelectronics and Nanoscience, Chalmers University of Technology and Göteborg University, Göteborg, SWEDEN.

Layers of GaN:Al, grown by solid-source, RF-plasma assisted MBE on sapphire (0001) substrates, have been studied. It has earlier been shown that GaN surface morphology can be improved during GaN MBE-growth by adding In as a surfactant, enhancing the migration of the impinging Ga-atoms on the surface. Our investigations revealed that Al, similarly to In, significantly improved the morphological, optical, and even electrical properties of the GaN. The incorporated concentration of Al, which ranged from 0.05% to several per cent, was measured by SIMS, while the layer quality was assessed by photoluminescence, Hall effect and high-resolution SEM. Microscopy revealed a meandering pattern and a surface roughness varying with the Al-content with the smallest surface roughness at 1.5Å. The free carrier concentration and mobility both varied with the Al-concentration with the best electrical properties for 0.15% Al, $3x10^{17}\ cm^{-3}$ and 140 $Vs/cm^2$. Photoluminescence gave one main peak attributed to the neutral donor-bound acceptor. Its energy- and peak intensity increased with Al-concentration, but with a local intensity maximum for 0.15% Al. At this concentration the PL emission had a minimum in the FWHM, 15 meV.

**W3.37**
STRUCTURE AND MORPHOLOGY CHARACTERS OF GaN GROWN BY ECR-MBE USING HYDROGEN-NITROGEN MIXED GAS PLASMA. Tsutomu Araki, Yasuo Chiba, Yasushi Nanishi, Ritsumeikan Univ, Dept of Photonics, Shiga, JAPAN.

We have demonstrated GaN growth by electron-cyclotron-resonance plasma-excited molecular beam epitaxy (ECR-MBE) using hydrogen-nitrogen mixed gas plasma ($H_2$-$N_2$ plasma) as a group-V source. The main objective of this work is to investigate the effect of hydrogen on structure and morphology of the GaN layers by transmission electron microscopy (TEM) and scanning electron microscopy. GaN layers were grown on (0001) sapphire substrates by ECR-MBE. After nitridation process, low temperature GaN buffer layers were grown at 450°C. In this study, GaN layers were grown by using two different group-V sources, which were simple nitrogen plasma ($N_2$ plasma) and $H_2$-$N_2$ plasma. It was found that remarkable change in surface morphology appeared by addition of $H_2$ to $N_2$ plasma. Although some pits were observed, the coalescence of GaN layers using $N_2$ plasma was better than that of $H_2$-$N_2$ plasma. In contrast, hexagonal columnar-like structure was mainly observed in the GaN layers using $H_2$-$N_2$ plasma. TEM results showed that the surface of GaN using $H_2$-$N_2$ plasma formed {10-11} facet. It is considered that facet formation is promoted by addition of $H_2$ to $N_2$ plasma. It is also confirmed that the coalescence of GaN layers using $H_2$-$N_2$ plasma was worse than that of $N_2$ plasma even at the very early stage of growth with a thickness of 13 nm. From these observations, it is considered that the structure of GaN layer using $H_2$-$N_2$ plasma was already determined at the early stage. Although their origins are little understood, this difference in structure and morphology of the GaN layers might be associated with the generation of $NH_x$ or $H_2$ related excited species in the $H_2$-$N_2$ plasma.

**W3.38**

DEPOSITION OF ZINC-BLENDE AlN FILMS ON Si(100) AND MgO(100) SUBSTRATES. Margarita P. Thompson, Dept. of Chemical Engineering and Materials Science, Gregory W. Auner, Dept. of Electrical and Computer Engineering, Wayne State University, Detroit, MI; Andrew R. Drews, Physics Dept., Scientific Research Laboratories, Ford Motor Company, Dearborn, MI; Tsvetanka S. Zheleva, Kenneth A. Jones, Sensors and Electron Devices Directorate, US Army Research Laboratory, Adelphi, MD.

AlN is a III-V nitride which occurs in the thermodynamically stable hexagonal wurtzite structure. There have been theoretical predictions for the occurrence of the cubic zinc-blende phase of AlN. To date very little is known about the physical, electrical, and optical properties of zinc-blende AlN since films with sufficient thickness and quality for such measurements have not been available. We report the first deposition of AlN films in the metastable cubic zinc-blende structure on Si(100) and MgO(100) substrates. The films were deposited by Plasma Source Molecular Beam Epitaxy (PSMBE). Zinc-blende AlN formed when the hollow cathode plasma source of the PSMBE system was powered by a pulse d.c. power supply. The films were epitaxial with respect to the Si(100) and MgO(100) substrates. Reflection High Energy Electron Diffraction (RHEED) showed that the films possess four-fold symmetry. X-Ray Diffraction (XRD) showed two strong peaks corresponding to zinc-blende AlN (200) and (400) reflections. Using the XRD data the lattice parameter of zinc-blende AlN was calculated to be 4.373ÅTransmission Electron Microscopy (TEM) studies indicated that the films are single crystalline and epitaxial to the substrates. No traces of the wurtzite structure were detected.

**W3.39**

STUDIES OF CUBIC GaN:Mg GROWN BY MOCVD ON GaAs(100). Da-peng Xu, Hui Yang, De-gang Zhao, Shun-feng Li, Rong-han Wu, National Research Center for Optoelectronics Technology, Institute of Semiconductors, Chinese Academy of Sciences, Beijing, CHINA.

Cubic GaN:Mg samples grown by MOCVD on GaAs (100) have been investigated in an attempt to gain insight into incorporation dependence of growth conditions. Secondary ion mass spectroscopy (SIMS) indicated that both ammonia and Mg flow-rates had effect on the incorporation of Mg atoms in GaN films. Increased incorporation of Mg with decreasing ammonia flow rates is attributed to N vacancies. Also, the optical properties of cubic GaN:Mg were investigated. The room photoluminescence (PL) spectra showed a broad blue Mg-related emission. As Mg concentration increased within some range, the near-band emission of GaN decreased, while the blue Mg-related emission increased. Beside a shallow acceptor level at 0.213eV, additional three Mg-related deep defect levels are found around 215 meV, 374meV, and 570 meV from the conduction band. However, the Mg concentration was too high, the emission efficiency decreased. This may be attributed to the increasing of nonradiative center under high Mg doping.

**W3.40**

ELECTRICAL PROPERTIES OF MBE-GROWN ZINCBLENDE InN AND GaN COMPOUND SEMICONDUCTORS. J.R.L. Fernandez, A. Tabata, J.R. Leite, A.P. Lima, Instituto de Fisica da Universidade de Sao Paulo, Sao Paulo , BRAZIL; V.A. Chitta, Universidade Sao Francisco, Itatiba, BRAZIL; E. Abramof, Instituto Nacional de Pesquisas Espaciais, Sao Jose dos Campos, BRAZIL; D.J. As, D. Schikora, K. Lischka, Universitat/GH Paderborn, Paderborn, GERMANY.

GaN-based heterostructures have been playing the major role on the successful fabrication of high-efficiency light-emitting diodes and lasers operating in the amber, green, blue and ultraviolet regions of the electromagnetic spectra[1]. Although the hexagonal form of the InGaN alloys is the active layer in these devices, the cubic form arises as a promising alternative since it can be more easily cleaved and doped[2]. In this work we deal with the cubic forms of InN and GaN compounds grown by MBE on GaAs(100) substrates. Control of the electrical properties of the nitrides has been one of the main challenges facing researchers in this field. Here we address this problem by measuring carrier concentrations and mobilities of unintentionally doped c-InN and c-GaN samples. Cubic GaN doped with silicon(n-type) and with magnesium(p-type) are also investigated. The experiments are carried out in the temperature interval 4 to 300K. The unintentionally doped c-InN sample displays relatively high n-type background carrier concentration probably originated from the nitrogen vacancy native defect or oxygen and silicon residual impurities. For the doped samples the measured carrier concentrations are correlated to the dopant beam equivalent pressure fixed during growth. The carrier concentrations and mobilities obtained for the zincblende InN and GaN samples are compared with the results obtained for the corresponding hexagonal nitride layers. [1] S. Nakamura, Science 281, 956 (1998). [2] J.W. Orton and C.T. Foxon, Rep. Prog. Phys. 61, 1 (1998).

**W3.41**

ARSENIC EFFECT FOR HEXAGONAL GROWTH-SUPPRESSION ON A CUBIC GaNAs GROWTH USING METALORGANIC CHEMICAL VAPOR DEPOSITION. S. Yoshida, T. Kimura, J. Wu, K. Onabe, Department of Applied Physics, The University of Tokyo, Bunkyo-ku, Tokyo, JAPAN; and Y. Shiraki, Research Center for Advanced Science and Technology, The University of Tokyo, Meguro-ku, Tokyo, JAPAN.

Such III-V-N materials as GaNAs and GaNP are very promising for light-emitting devices over a wider range of wavelength due to huge bandgap bowing. It has recently been reported that N-rich hexagonal GaNAs (h-GaNAs, As<0.5%) and GaNP (h-GaNP, P<1.5%) could be grown on a sapphire substrate by gas-source molecular-beam epitaxy. However, there is a serious problem involving the difference in the stable crystal structures of GaN (wurtzite) and GaAs (zincblende), resulting in a growth-difficulty of this alloy. There have been no reports concerning the growth of N rich cubic GaNAs (c-GaNAs) and GaNP (c-GaNP). We report on As-suppression effects of hexagonal GaNAs in a c-GaNAs epitaxial layer and the characterization of GaNAs grown by metalorganic chemical-vapor deposition (MOCVD). A thin buffer layer (20 nm) was first grown on a substrate at 580°C using trimethylgallium and dimethylhydrazine (DMHy), and GaNAs samples were grown at different $AsH_3$ flow rates (0∼450 $\mu$mol/min) at 920°C. As a result, three types of surface morphologies were obtained: the first was obtained as a smooth surface ($AsH_3$= 0 $\mu$mol/min); the second was a mirror-like surface having small and isotropic grains (45 $\mu$mol/min $\leq$ $AsH_3$ $\leq$ 225 $\mu$mol/min); and the third involved three-dimensional surface morphologies ($AsH_3$ $\geq$ 450 $\mu$mol/min). Furthermore, it was confirmed using X-ray diffraction that the mixing ratio of hexagonal GaNAs in cubic GaNAs decreased with an increase of $AsH_3$ flow rate. We could obtained a GaNAs having a cubic component above 85% at $AsH_3$ flow rates above 90 $\mu$mol/min. Therefore, the MOCVD growth method using $AsH_3$ and DMHy was effective for suppressing hexagonal GaNAs.

**W3.42**

SYNTHESIS OF (InGa)(AsN) ALLOYS BY ION IMPLANTATION. S. Clarke, S. Ghaisas, and R.S. Goldman, Department of Materials Science and Engineering; V.H. Rotberg and B. Mech, Department of Nuclear Engineering and Radiological Sciences; Roy Clarke, Department of Physics University of Michigan, Ann Arbor, MI.

Mixed-anion nitride-arsenide compound semiconductor alloys and nanostructures are promising for a variety of novel optoelectronic devices. To date, their synthesis has involved epitaxial growth and limited studies have been performed using ion implantation.[1] We present new results on InGaAsN alloys synthesized by $N^+$ ion implantation into GaAs, InAs, and InGaAs-based heterostructures. Using a variety of implantation and rapid thermal annealing conditions, we have been able to obtain several different nitride-arsenide phases. Rutherford Backscattering spectrometry suggests significant nitrogen incorporation into the samples. Using four-circle x-ray diffraction with a rotating anode source, we have found evidence of coexisting oriented cubic and hexagonal phases of GaNAs in implanted and annealed GaAs. The cubic GaNAs phases range in composition from 77 to 88% N and are oriented 9° away from the GaAs substrate. Our data also suggests the formation of a

hexagonal phase of InN in the implanted and annealed InAs. The effects of various implantation and annealing conditions on the formation of InGaAsN alloys will be discussed. Microstructural and optical studies by transmission electron microscopy and photoluminescence will also be presented. [1] X.W. Lin, M. Behar, R. Maltez, W. Swider, Z. Liliental-Weber, and J. Washburn, Appl. Phys. Lett. 67, 2699 (1995)

**W3.43**
METAL ORGANIC VAPOR PHASE EPITAXY (MOVPE) OF GaAs/GaAsN/GaAs QUANTUM WELLS USING TERTIARYBUTYLHYDRAZINE. Torsten Schmidtling, Michael Klein, Udo W. Pohl, W. Richter, Tech. Univ. of Berlin, Inst of Solid State Physics, Berlin, GERMANY.

Devices for optical fibre communication operating in the 1.3 and 1.55 micron spectral range require low bandgap materials. Due to the large bandgap bowing of GaAsN, this can be achieved for GaAs based devices by alloying GaAs with nitrogen. However, incorporation rates beyond a few percent have been difficult to obtain in MOVPE at the high temperatures necessary for decomposition of the standard N-sources. Progress has been recently reported by several authors using dimethylhydrazine (DMHy) which has a low decomposition temperature of 400°C. Tertiarybutylhydrazine (TBHy) has an even lower decomposition temperature of 300°C [U.W.Pohl *et al.*, Mat.Sci.Engin.B **59**(1999)20] due to a comparably weak tertiarybutyl-nitrogen bond. Thus it appears suitable to achieve an even higher nitrogen content. Moreover, a lower carbon incorporation as compared to DMHy has also been reported for GaN epilayers grown with TBHy [U.W.Pohl *et al.*, Jpn.J.Appl.Phys.**38**(1999)L107]. We have grown coherently strained GaAs/GaAsN/GaAs quantum wells under various growth conditions using both tertiarybutylarsine (TBAs) or arsine as As precursors. The good structural quality of the samples was proven by X-ray diffraction. We found an increase of the nitrogen incorporation with decreasing growth temperature, similar to the growth with DMHy. At low partial pressure of TBHy, the effect of using either TBAs or arsine as arsenic precursor on the nitrogen content is found to be small. A high nitrogen content of about 7% was achieved using TBAs at a comparably high nitrogen partial pressure ratio of TBHy/(TBHy+TBAs) near 0.9 and low growth temperatures of typically 530°C. The photoluminescence intensity decreases with increasing nitrogen content but recovers after annealing. Atomic force microscopy of thick, partially relaxed GaAsN layers provides clear indication that the use of TBHy, even at high nitrogen contents, does not affect the morphology of the epilayers.

**W3.44**
DIFFUSION OF NITROGEN FROM A BURIED DOPING LAYER IN INTRINSIC GALLIUM ARSENIDE INVESTIGATED BY THERMAL ANNEALING OF GaAs/GaAs:N/GaAs HETEROSTRUCTURES. G. Bösker, N.A. Stolwijk, H. Mehrer, Inst f Metallforschung, Univ Münster, Münster, GERMANY; J.V. Thordson, U. Södervall, T.G. Andersson, Dept of Physics, Chalmers Univ of Technology and Göteborg Univ, Göteborg, SWEDEN; Ch. Jäger, W. Jäger, Mikrostrukturanalytik, Tech Fak d Univ Kiel, Kiel, GERMANY.

In recent years the technical application of GaAs/GaN systems as lasering systems has attracted much attention. Still many problems concerning grown-in defects, lifetime, and thermal stabilty remain. This inspired us to undertake the present investigations on GaAs/GaAs:N/GaAs heterostructures, which were grown on GaAs wafers by solid-source molecular beam epitaxy and $N_2$ excitation by an rf plasma source. Maximum N concentrations in the N-enriched layer where kept in the range between $10^{19}$ cm$^{-3}$ and $10^{20}$ cm$^{-3}$ to minimize grown-in defects. Transmission-electron microscopy (TEM) was used to check the absence of grown-in and diffusion-induced microstructural defects in the samples after diffusion. The nitrogen distribution before and after annealing was determined by secondary-ion mass spectroscopy (SIMS). Profile broadening of the N peaks was numerically simulated within the program package ZOMBIE. The markedly non-Gaussian shape of the N distribution after isothermal annealing can be excellently described within the framework of the kick-out mechanism, which involves As interstitials ($I_{As}$), N-atoms substitutionally incorporated on the As sublattice ($N_s$) and interstitially dissolved N-atoms ($N_i$). For the first time data concerning N diffusion and As diffusion were obtained in the technologically important temperature range of 724 – 922 °C. In general, the present findings contribute to studies concerning the thermal stability of more complex GaAs/GaN systems.

**W3.45**
IN-SITU MONITORING OF GaN METAL ORGANIC VAPOR PHASE EPITAXY BY SPECTROSCOPIC ELLIPSOMETRY IN THE DEEP UV. Sven Peters, SENTECH Instr. GmbH, Berlin and Techn. Univ. Berlin, GERMANY, Torsten Schmidtling, U.W. Pohl, J.-T. Zettler and W. Richter, Techn. Univ. Berlin, GERMANY.

Spectroscopic Ellipsometry in the VIS-UV spectral range is a highly sensitive and well established tool for measuring the optical properties of semiconductors. For wide-bandgap semiconductors an extension of the spectral range into the deep UV up to 6.5 eV is required. In order to monitor in-situ the growth of hexagonal GaN on basal plane sapphire we attached a deep-UV-ellipsometer to a MOVPE reactor. Both, ammonia ($NH_3$) and tertiarybutylhydrazine (tBHy) were used as nitrogen precursors. For reference purpose the dielectric function of hexagonal device grade GaN was measured between RT and 1060°C. In-situ spectra were taken during the different growth steps necessary for successful GaN epitaxy: annealing of the substrate, nitridation, deposition and annealing of the GaN buffer layer and growth of the GaN overlayer. Nitridation was found to start at about 830°C and results in an approximately 2 nm thick AlN layer formed on top of the sapphire substrate. An optimized buffer layer thickness of 25 nm was determined from our in-situ measurements. The kinetics of the transformation from the amorphous to a crystalline state turned out to be the key parameter for the quality of the subsequently grown GaN layer. Furthermore, a distinct effect of susceptor pretreatment with respect to the onset of buffer nucleation was found. Using the ellipsometric information recorded in-situ, we were able to significantly improve the surface morphology and crystal quality of the GaN epilayers.

**W3.46**
BRITTLE/DUCTILE RELAXATION KINETICS OF COHERENTLY STRAINED AlGaN ON GaN. S.J. Hearne, J. Han, S. Lee, J.A. Floro, D. Follstaedt, Sandia National Labs., Albuquerque, NM; E. Chason, Div. of Engineering, Brown Univ., Providence RI; I.S.T. Tsong, Dept. of Physics and Astronomy, Arizona State Univ., Tempe, AZ.

AlGaN grown heteroepitaxially on GaN is in tension, which limits the device structures that can be fabricated before cracking occurs. We explored the kinetics of stress relaxation in this system by incorporating an in situ stress monitor onto a metal-organic chemical vapor deposition reactor. The stress measurements were correlated with ex situ microstructural techniques to characterize the nature of the stress relaxation. Both, catastrophic and slow continuous stress relaxation occurred during deposition, depending on the available driving force. While cracking (brittle failure) clearly occurred in response to the tensile stress, the density was too low to account for the complete relief that we observed. We found that a high density of misfit dislocations were present at the ALGaN / GaN interface. We will discuss the interplay between cracking and dislocations in relieving the coherency stress.

**W3.47**
TEM STUDY OF THE MORPHOLOGY OF GaN/SiC (0001) GROWN AT VARIOUS TEMPERATURES BY MBE. W.L. Sarney, L. Salamanca-Riba, Dept. Of Materials & Nuclear Engineering, University of Maryland, College Park, MD; V. Ramachandran, A.R. Smith, R.M. Feenstra, Dept. of Physics, Carnegie Mellon University, Pittsburgh, PA; D.W. Greve, Dept. of Electrical & Computer Engineering, Carnegie Mellon University, Pittsburgh, PA.

GaN films have been grown on SiC (0001) by MBE at various substrate temperatures (550 - 700 C) and characterized by RHEED, STM, x-ray diffraction, AFM and TEM. This study focuses on TEM observations of the films' features, such as stacking faults and dislocations, which are related to the substrate temperature. The film morphology was imaged using high resolution TEM (HRTEM) at 300 kV and multiple dark field conditions. We find the dislocation density of the films decreases as the substrate temperature increases. In particular, we find that a much higher density of basal plane stacking faults and screw dislocations for samples grown at low temperatures compared to those grown at high temperatures. In agreement with the TEM analysis, AFM observations indicate that the concentration of spiral growth mounds decreases with increasing substrate temperatures. Spiral growth mounds are known to arise from screw dislocations emerging at the film surface. Basal plane stacking faults can lead to the generation of double-positioning boundaries (DPB's) and prismatic stacking faults. Since basal plane defects are more abundant for samples grown with low substrate temperatures, they also contain a higher density of vertical defects. Despite the presence of various defects, x-ray analysis shows that the GaN films are of high quality. The rocking curve full width at half maximum (FWHM) is between 1 and 2 arc-minutes for all of the films we examined. The double crystal rocking curves and the triple crystal diffractograms showed Pendellosung fringes for films 200 nm in thickness. Furthermore, the FWHM for the GaN (0002) peak decreases with increasing growth temperature. In agreement with the x-ray analysis, the TEM images show that the film quality improves with increasing growth temperature. We will discuss the different types of defects seen in the TEM images and how the defect morphology are related to the growth temperature.

**W3.48**
RECOMBINATION AND SCATTERING AT DISLOCATIONS IN Si-DOPED AlGaN. Martin Albrecht, J. Krinke and Horst P.Strunk, Universitaet Erlangen-Nuernberg, Institut fuer Werkstoffwissenschaften, Mikrocharakterisierung, Erlangen, GERMANY. A.Cremades, J.M. Ulloa, J. Piqueras, Dpto. Fisica de Materiales, Unversidad Complutense de Madrid, Madrid, SPAIN; C.Zanotti-Fragonara, G.Salviati, CMR-MASPEC, Parma ITALY.

We analyse the recombination and scattering mechanisms of carriers at dislocations and the influence on the minority carrier diffusion length in Si doped heteroepitaxial GaN and AlGaN layers. Our study is based on the combined use of transmission electron microscopy (conventional and at high resolution), electron beam induced current (EBIC), and cathodoluminescence (CL) in the scanning (transmission) electron microscope. EBIC reveals recombination active centres, the activity of which increases with increasing injection conditions and also with decreasing temperature of the measurement. CL measurements of such samples show a corresponding increase of the donor acceptor pair transitions with injection. This behaviour can be understood in the framework of the Shockley-Read-Hall recombination theory, assuming dislocations to induce shallow acceptor levels in the band gap (20 meV). We discuss the influence of the strain field of the dislocation (i) on bend bending and (ii) on the formation of a piezoelectric fields sperately. We present measurements by electron holography of the strain induced field arround the dislocation, and dicuss these fields with respect to gettering of the intrinsic atomic defects.

**W3.49**
INVESTIGATING THE ATOMIC SCALE STRUCTURE-PROPERTY RELATIONSHIPS AT DISLOCATION CORES IN UNDOPED/DOPED GaN AND AlGaN. Y. Xin, I. Arslan, N.D. Browning, University of Illinois at Chicago, Department of Physics, Chicago, IL; S.J. Pennycook, Oak Ridge National Laboratory, Solid State Division, Oak Ridge, TN.

The apparent insensitivity of the properties of III-nitride thin films to the presence of significant numbers of threading dislocations has led to the rapid development of these materials for short wavelength LEDs and lasers. Although modern epitaxial layer overgrowth techniques have now reduced the number of dislocations to extremely low levels, the structure-property relationships at dislocation cores are still of fundamental interest and can have a far reaching impact on our understanding of the intrinsic and extrinsic doping mechanisms in these compounds. Here we report an atomic resolution experimental study of undoped/doped dislocation cores in GaN and AlGaN. Using the Z-contrast imaging technique in the scanning transmission electron microscope (STEM), direct images of the cores reveal that in all cases (doped/undoped, GaN/AlGaN) pure edge and mixed edge/screw dislocations have full cores. The Z-contrast images show that these cores exhibit an 8-fold ring, in which the core column has the same configuration as one row of dimers on the {10-10} surface. Atomic resolution electron energy loss spectra (EELS) taken from this core column indicate that there are significant changes in the local electronic structure associated with this core structure (as measured from the nitrogen K-edge). Simulations of the core structure/energy loss spectrum using a simple ionic model/multiple scattering analysis with self-consistent potentials, indicate that the observed changes in electronic structure are representative of stoichiometric cores, i.e. without the presence of high concentrations of Ga or N vacancies. Furthermore, analysis of the doped films reveals that there is no segregation of the dopants to the dislocation cores (within the detection limits of the technique). Such preliminary results indicate that models for the effect of doping on the properties of dislocations should not implicitly contain segregation of significant levels of impurities or point defects to the cores.

**W3.50**
MICROSTRUCTURE AND OPTICAL PROPERTIES OF GaN FILMS ON SAPPHIRE SUBSTRATES. Zhizhong Chen, Jianming Zhu, Bo Shen, Rong Zhang, Yugang Zhou, Peng Chen, Weiping Li, Wenjun Liu, Zhenlin Wang, Youdou Zheng and Shusheng Jiang, Department of Physics and National Laboratory of Solid State Microstructures, Nanjing University, Nanjing, PR CHINA.

Transmission electron microscope (TEM), double crystal x-ray diffraction (XRD), photoluminescence (PL) and Raman scattering measurement were applied to study the correlation between the microstructure and material properties of the GaN films grown by light radiation heating metalorganic chemical vapor deposition (LRH-MOCVD), using GAN buffer Layer on sapphire substrates. Corresponding to the density of the threading dislocation (TD) increasing about one order, the yellow luminescence (YL) intensity was strengthened from negligible to two orders higher than the band-edge emission intensity. The full width of half maximum (FWHM) of GaN (0002) peak of the XRD rocking curve was widened from 11 min to 15 min, and in Raman spectra, the E2 mode is broadened. A zippers-structure of GaN buffer layer was discovered by high-resolution electron microscope (HREM). This structure is likely to lower both the structural and optical qualities of GaN films. Furthermore we explore the origins of TD and relationship between the zipper-structure and the epilayer growth model.

**W3.51**
EFFECT OF HIGH PRESSURE ANNEALING ON THE DENSITY OF DISLOCATIONS IN HETEROEPITAXIAL GaN LAYERS. Dmitro Kolesnikov, Witold Lojkowski, Jan Jun, High Pressure Research Center-Unipress, Warsaw, POLAND; Piotr Dluzewski, Institute of Physics, Polish Academy of Sciences, Warsaw, POLAND.

Heteroepitaxial layers of GaN on sapphire have been annealed at temperatures up to 1630K under a pressure of 1 GPa of nitrogen. The dislocations in the layers have been observed by means of Transmission Electron Microscopy as a function of annealing temperature. It was found that the density of dislocations decreases when the temperature is above 1530K. Observations of cross sections of the specimens have shown that the density of dislocations parallel to the surface decreased considerably. Plan view observations revealed ordering of the dislocations. The above result shows that dislocations become mobile in this material at relatively low temperatures and that high pressure annealing might be used to decrease the density of dislocations in this material.

**W3.52**
THE EVOLUTION OF LATTICE STRUCTURE OF GaN NUCLEATION LAYER DURING INITIAL STAGE MOCVD GROWTH. Chong Cook Kim, Jung Ho Je, Pohang Univ, Dept of Materials Science and Engineering, Pohang, KOREA; Min-Su Yi, Do Young Noh, Kwangju Institute of Science and Technology, Dept of Materials Science and Engineering and Center for Electronic Materials Research, Kwangju, KOREA.

The evolution of lattice structure of GaN nucleation layers during the initial growth process of MOCVD was investigated by synchrotron x-ray scattering measurements. The nucleation layer grown at low temperature of 560°C was predominantly cubic GaN with the lattice constant a=4.508Å. As the film was annealed to 1100°C, the cubic GaN transformed into disordered hexagonal GaN with decreased GaN atomic layer spacing (c=5.185Å, a=3.186Å). Both the as-grown and the annealed nucleation layer contain small amount of extremely well aligned domains that are tensile strained. The in-plance lattice spacing of the nucleation layer does not change during annealing process as well as during subsequent growth of epitaxial GaN at 1100°C.

**W3.53**
DIRECT DETERMINATION OF THE COMPOSITION AND ELASTIC STRAIN IN InGaN AND AlGaN LAYERS. A. Vantomme, M.F. Wu, S. Hogg, G. Langouche, Instituut voor Kern- en Stralingsfysica, University of Leuven, BELGIUM; S. Yao, Dept of Technical Physics, Peking University, Beijing, PR CHINA; K. Jacobs, I. Moerman, Dept of Information Technology, University of Gent-IMEC, BELGIUM; J. Li, G.Y. Zhang, Dept of Physics, Mesoscopic Physics Lab., Peking University, Beijing, PR CHINA.

Due to their lattice mismatch with the GaN buffer on which they are grown, most heteroepitaxial InGaN and AlGaN layers are (at least partially !) elastically strained. This elastic strain is an important parameter, since it influences the optical as well as the structural properties of the nitride. Hence, it is surprising that so far, the study of the elastic strain received scant attention. To determine the strain, the In (or Al) composition of the alloy has to be known precisely. In most cases, this is done using either X-ray diffraction (XRD) or photoluminescence. However, to extract the composition from these measurements, assumptions have to be made concerning the coherency or concerning the bandbowing of the epilayer. Since these parameters are not always well known, neither always controlable, large errors on the composition can be obtained. Alternatively, we used Rutherford backscattering spectrometry (RBS) to directly and unambiguously determine the composition of the nitride alloys. Since RBS is based on collisions of energetic atoms, its results are not biased by variations in strain and/or optical and electrical properties. Moreover, when using backscattering in channeling geometry, information on the crystallinity and the elastic strain is obtained. A combination of XRD and RBS/C was used to study the strain in InGaN and AlGaN films grown on GaN/sapphire. These ternary nitrides exhibit a positive or negative lattice mismatch respectively, with respect to the GaN buffer. First, the In (resp. Al) composition was determined using RBS, enabling us to accurately calculate the bulk lattice parameters. Subsequently, by combining XRD and channeling, the perpendicular and parallel strain could be determined quantitatively. As expected, the InGaN layer is under compressive strain, while the AlGaN layer is under tensile strain in the parallel direction. The results will be compared to strain data for GaN layers.

**W3.54**
STRUCTURAL ANALYSIS OF (GaIn)(NAs)/GaAs MQW STRUCTURES GROWN BY MOVPE. C. Giannini, L. Tapfer, Pastis-CNRSM, Brindisi, ITALY; F. Hohnsdorf, J. Koch, W. Stolz, Materials Science Center, Philipps-University, Marburg, GERMANY.

(GaIn)(NAs) alloys grown on GaAs substrates offer the unique possibility to realize optoelectronic devices for the wavelength emission in the range of 1300-1550 nm due to the large band gap bowing. However, this material system exhibits a large miscibility gap under thermodynamic equilibrium conditions. Therefore, extreme non-equilibrium conditions at low growth temperatures are required in order to maintain homogeneous epitaxial deposition for the metastable (GaIn)(NAs) material system. In this work, we investigate the structural properties of (GaIn)(NAs) epitaxial layers and (GaIn)(NAs)/GaAs-MQW grown at low temperature by metalorganic vapour phase epitaxy (MOVPE) using triethylgallium (TEGa), trimethylindium (TMIn), tetriarybutylarsine (TBAs) and 1,1-dimethylhydrazine (UDMHy). The structural properties were investigated by means of high-resolution x-ray diffraction (HRXRD), reciprocal space mapping (RSM) and secondary ion mass spectrometry (SIMS). In particular, the In- and N-incorporation, the lattice strain fields (strain tensor components) and strain modulation profile and the structural perfection of the metastable (GaIn)(NAs) material system are studied in detail by comparison between HRXRD and SIMS data. Under optimized epitaxial deposition conditions high-quality MQW structures with In-concentrations up to 32% and N-contents up to 4% could be realized both lattice matched as well as strained on GaAs substrate. The high structural quality and crystalline perfection are demonstrated by the excellent agreement between experimental and simulated HRXRD patterns. Sharp satellite peaks up the 40th order indicate a good interface quality. However, peak broadening and diffuse scattering in RSM, observed for samples with N-concentrations larger than 4%, indicate a deterioration in epitaxial layer quality. These x-ray diffraction evidences can be explained by assuming a mosaic structure of the epitaxial layers, probably caused by clustering phenomena.

**W3.55**
FORMATION MECHANISM AND RELATIVE STABILITY OF DISLOCATIONS AND PRISMATIC STACKING FAULTS IN WURZITE (Al, Ga, In) NITRIDES. Jun Chen, Nadir Aochoune, Genard Nouet and Pierre Ruterana, Laboratoire d'Etudes et de Recherches sur les Matriaux, UPRESA CNRS 6004, ISMRA, Caen, FRANCE.

The active layers of GaN grown on SiC or sapphire contain high densities of threading dislocations. Using high resolution electron microscopy, anisotropic elasticity calculations and image simulations, typical contrast was identified for these defects. The atomic structure of the edge threading dislocations was found to exhibit 5/7, 8, or 4/6 atom cycles. The first two configurations were observed at a similar frequency for isolated dislocations and low angle boundaries. The 4 atom ring configuration was identified in high angle grain boundaries. Energetic calculations show that the three configurations have similar formation energies in GaN, which probably explains their observation. The formation of the {1-210} stacking fault, which has two atomic configurations in wurtzite (Ga,Al,In)N, has been investigated by high resolution electron microscopy and energetic calculations. It originates from steps at the SiC surface and it can form on a flat (0001) sapphire surface. The relative stability of the two atomic configurations was investigated by energetic calculations. It was found that they have comparable energy in AlN, whereas the $1/2< 10-11 >$\{1 -210\} atomic configuration should be more stable in GaN and InN. Experimental evidence is shown in the case of AlN and GaN from high resolution electron microscopy. Observations carried out in plan-view show the $1/2< 10-11 >$\{1-210\} atomic configuration in GaN layers. The $1/6< 20-23 >$ configuration was found in small areas inside the AlN buffer layer in cross section observations. It folds rapidly to the basal plane, and when back into the prismatic plane, it bears the $1/2< 10-11 >$\{1-210\} atomic configuration.

**W3.56**
THREADING DISLOCATION DENSITY REDUCTION IN GaN/SAPPHIRE HETEROSTRUCTURES. A.K.Sharma, A. Kvit and J. Narayan, NSF Center for Advanced Materials and Smart Structures; Department of Materials Science and Engineering, North Carolina State University, Raleigh, NC.

Large lattice mismatch between GaN and $\alpha$-$Al_2O_3$ (15%) leads to the possibility of high threading dislocation densities in the nitride layers grown on sapphire. This article threading defect reduction in GaN epitaxial thin layer was investigated as a function of processing variables. The microstructure changes from threading dislocations normal to the basal plane to stacking faults in the basal plane. The plan-view TEM and the corresponding selected-area diffraction pattern show that the film is single crystal and is aligned with a fixed epitaxial orientation to the substrate. The epitaxial relationship was found to be $(0001)_{GaN}\|(0001)_{Sap}$ and $[01\bar{1}0]_{GaN}\|[\bar{1}2\bar{1}0]_{Sap}$. This is equivalent to a 30° rotation in the basal (0001) plane. This film is found to contain a high density of stacking faults with average spacing 15 nm terminated by partial dislocations. The density of partial dislocations was estimated from plan-view TEM image to be $7x10^9$ $cm^{-2}$. The cross-section image of GaN film shows the density of stacking faults is highest in the vicinity of the interface and decreases markedly near the top of the layer. Inverted domain boundaries, which are almost perpendicular to the film surface, are also visible. The concentration of threading dislocation is relatively low ($\sim 2x10^8$ $cm^{-2}$), compared to misfit dislocations. The average distance between misfit dislocations was found to be 22 Å. Contrast modulations due to the strain near misfit dislocations are seen on high-resolution cross-sectional TEM micrograph of GaN/$\alpha$-$Al_2O_3$ interface. This interface is sharp and does not contain any transitional layer. The near interfacial region has a high density of Shockley and Frank partial dislocations. Mechanism of accommodation of tensile, sequence and tilt disorder through partial dislocation generation is discussed. In order to achieve low concentration of threading dislocations we need to establish favorable conditions for some stacking disorder in thin layers above the film-substrate interface region.

**W3.57**
SEM STUDIES OF GaN FILMS PREPARED BY HVPE. A.Y. Polyakov, A.V. Govorkov, N.B. Smirnov, M.G. Mil'vidskii, Institute of Rare Metals, Moscow, RUSSIA; D.V. Tsvetkov, S.I. Stepanov, A.E. Nikolaev, A.F. Ioffe Fiziko-Technical Institute RAS, St.-Petersburg, RUSSIA; V.A. Dmitriev, TDI, Inc., Gaithersburg, MD.

Two GaN films with the thickness of 3 microns and 20 microns were grown by HVPE on sapphire and a 0.5 microns-thick GaN film was grown by HVPE directly on SiC. The samples were characterized by MCL and EBIC measurements. The surface of the 3-micron GaN/sapphire film was found to be featureless, while the surface of the 20-micron GaN/sapphire sample showed the presence of crescent-like growths. Combination of MCL spectra measurements and of MCL and EBIC imaging of such growths regions allows to conclude that these regions have a higher concentration of residual donors and a lower density of donor-acceptor pairs (DAP) and of stacking faults and/or screw dislocations. In addition to these nonuniformities both GaN/sapphire samples show the presence of mosaic nonuniformity in MCL and EBIC which is not related to any morphological features. The diffusion length measurements on these samples give the values of 2-3 microns. The most interesting feature of the MCL images of the GaN/SiC sample is the presence of small spots producing reverse contrast in the bandedge (dark spots) and DAP (bright spots) luminescence indicating that the density of residual acceptors could be enhanced in such regions. The density of the spots (about $10^7$-$10^8$ $cm^{-2}$) is comparable to the density of screw dislocations in the sample. EBIC imaging of this sample revealed the presence of a network of dark line defects that somewhat tentatively are attributed to the misfit dislocations at the GaN/SiC interface.

**W3.58**
MICROSTRUCTURAL INVESTIGATIONS ON GaN FILMS GROWN BY LASER INDUCED MOLECULAR BEAM EPITAXY. H.Zhou, F. Phillipp, Max-Planck-Institut fuer Metallforschung, Stuttgart, GERMANY.

Microstructural investigations on GaN films grown on SiC and sapphire substrates by laser induced molecular beam epitaxy have been performed. Threading dislocations with Burgers vectors of $1/3<11\bar{2}0>$, $1/3<11\bar{2}3>$ and [0001] are typical line defects, predominantly the first type of dislocations. Their densities are typically $1.5\times10^{10}cm^{-2}$ and $4\times10^9$ $cm^{-2}$ on SiC and sapphire, respectively. Additionally, planar defects characterized as inversion domain boundaries lying on $\{1\bar{1}00\}$ planes have been observed in GaN/sapphire samples with an inversion domain density of $4\times10^9cm^{-2}$. The inversion domains are of Ga-polarity with respect to the N-polarity of the adjacent matrix. However, GaN layers grown on SiC show Ga-polarity. Possible reasons for the different morphologies and structures of the films grown on different substrates are discussed. Based on an analysis of displacement fringes of inversion domains, an atomic model of the IDB-II with Ga-N bonds across the boundary was deduced. High resolution transmission electron microscopy observations and the corresponding simulations confirmed the IDB-II structure determined by the analysis of displacement fringes.

**W3.59**
INVESTIGATIONS OF (In,Ga)N/GaN MULTIQUANTUM WELL STRUCTURES BY GRAZING INCIDENCE X-RAY DIFFRACTION AND REFLECTIVITY TECHNIQUES. Jurgen Blaesing, Alois Krost, Otto-von-Guericke University, Institute of Experimental Physics, Magdeburg, GERMANY; Michael Heuken, AIXTRON AG, Aachen, GERMANY.

A series of InGaN/GaN multiple quantum well stacks was grown at different temperatures for the quantum wells and barriers by low-pressure metal organic chemical vapor deposition on 2 $\mu$m GaN/c-sapphire substrates. With appropriate growth conditions layer structures with mirror-like surfaces are obtained as evaluated by atomic force microscopy. The diffraction pattern in the neighbourhood of the GaN (0002) Bragg reflection shows up to 10 clearly resolved superlattice peaks and total thickness interfernce fringes demonstrating the excellent quality of the 5- or 10-fold (InGaN/GaN) MQW stacks. Grazing-incidence X-ray diffraction and X-ray reflectivity are used to investigate the in-plane lattice constant and the surface and interface roughness, respectively. Depending on In content and layer thickness, the structures are fully strained, partially relaxed, or totally relaxed with strongly inhomogeneous In and strain distribution including phase separation effects. From simulations of the pure specular reflectivity a surface and interface roughness of $\sim$0.7 nm was found for the best sample. The specular intensity is spread over an omega-range of 0.3° with a Gaussian distribution and a constant broadening over the whole 2 theta-range. The mapping of this specular reflectivity and the results from the (0002) and (30-30) omega-scans suggest a columnar structure model, whereby the individual columns are tilted by $< 0.15°$ with respect to each other. The rotation of the individual crystallites around the surface normal is typically 0.3°.

**W3.60**
SAMPLE CURVATURE AS A FUNCTION OF REMAINING SUBSTRATE THICKNESS FOR GALLIUM NITRIDE/LITHIUM GALLATE. S.R. Stock[1], W.A. Doolittle[2], A. Taylor[3], P. Kohl[3] and A.S. Brown[2]; [1]School of Materials Science and Eng., [2]School of Electrical and Computer Eng. or [3]School of Chemical Eng., Georgia Institute of Technology, Atlanta GA.

Obtaining undamaged thin films is crucial if thin film/compliant substrate processing is to be realized. Sometimes, however, gallium nitride thin films crack when the underlying lithium gallate substrate is chemically removed. This work reports x-ray rocking curved mapping of the response of the gallium nitride thin film and the lithium gallate substrate to the chemical removal of the back surface of the substrate. Influence of the thin film and substrate crystallography is discussed.

**W3.61**
PARTIALLY ORDERED AlGaN ALLOYS; GROWTH AND OPTOELECTRONICS PROPERTIES. E. Iliopoulos, M. Misra, D. Korakakis, T.D. Moustakas, Boston Univ., E.C.E. Dept. and Center for Photonics Research, Boston, MA; K.F. Ludwig Jr., Boston Univ., Dept of Physics, Boston, MA; C.B. Lioutas, Aristotle Univ. of Thessaloniki, Thessaloniki, Greece; L.H. Robins, National Institute of Standards and Technology, Gaithesburg, MD.

Long range atomic ordering has recently being reported in AlGaN and InGaN alloys, grown by both MBE and MOCVD. In both systems ordering occurs in the closed packed (0001) planes during growth in the [0001] direction, a result which is inconsistent with findings in cubic alloys. In this paper we present our studies of the growth of either spontaneously formed ordered AlGaN alloys or artficially formed superlattices on sapphire substrates by MBE. The structure and microstructure of these alloys has been investigated by studuing the superlattice peaks using X-ray diffraction and transmission electron microscopy. The appearance of forbidden (0001) Bragg reflections for these wurtzite type structures is a strong evidence of ordering along the (0001) direction. As expected the degree of ordering is maximum at 50% AlN mole fraction. To test the recent model proposed by Northrup and co-workers(1), that ordering occurs by preferential attachments of Ga(Al) atoms in the bilayer of $(10\bar{1}1)$ microfacets, we have prepared by the VPE method sapphire/GaN substrates with corrugated $(10\bar{1}1)$ facets. The growth of AlGaN alloys on such substrates is under current study. The optoelectronic properties were studied by optical absorption, photoconductivity and cathodoluminescence measurements. The optical energy gaps of ordered alloys with 50% AlN mole fraction are about 500 meV less than disordered alloys. The $(\mu\tau)$ products of partially ordered AlGaN alloys with 50% AlN mole fraction is about 2 orders of magnitude larger than corresponding $(\mu\tau)$ products of GaN films. This unexpected result is accounted for by very significant increase in the recombination lifetime due to carrier separation in the valence and conduction band of the ordered and disordered domains. (1) J.E. Northrup, L.T. Romano and J. Neugenbauer, Appl. Phys. Lett. 74, 2319 (1999)

**W3.62**
THE TEMPERATURE DEPENDENCE OF THE THERMAL CONDUCTIVITY OF LEO GALLIUM NITRIDE. Chongyang Luo, Hugues Marchand, D.R. Clarke, S.P. DenBaars, U.C. Santa Barbara, Santa Barbara, CA.

The thermal conductivity of LEO GaN films has been measured using an electrical harmonic technique. At room temperature, the thermal conductivity is at least 1.55 W/cm•K. This compares with the value of 1.30 W/cm•K reported for bulk single crystal material at room temperature and the same value we have measured for a HVPE thick film grown on sapphire with no nucleation layer. The temperature dependence of the thermal conductivity up to 100°C will be reported and compared with existing theory. Also, for comparison, the thermal conductivity of the sapphire substrate and a variety of other semiconductors (Si, GaAs and InP) will be reported.

**W3.63**
ENERGETICS OF BULK GaN: HEAT OF FORMATION AT 298 K. Mandar R. Ranade, Franck Tessier, Alexandra Navrotosky, Valerie J. Leppert, Subhash H. Risbud, UC Davis, Dept. of Chemical Engineering and Materials Science, Davis, CA; Francis J. DiSalvo, Cornell University, Ithaca, NY; Cengiz M. Balkas, Sterling Semiconductor Inc., Sterling, VA.

High temperature oxide melt drop solution calorimetry determined the heat of formation of bulk GaN as -156.8 ± 16.0 kJ/mol. This new calorimetric value is in agreement with that determined from equilibrium pressure studies of nitrogen over solid GaN, -157.7 kJ/mol. The heat of formation of GaN obtained through combustion calorimetry, -110 kJ/mol, was used widely and appears to be incorrect. The heat of drop solution varies significantly for the several samples studied. All samples were characterized by XRD, BET, particle size analysis, and chemical analysis and showed deviation from the ideal stoichiometric nitrogen content with varying amounts of O impurity. As N is the major component of GaN and causes the large exothermic heat of oxidation in our thermochemical cycle, we plotted the calorimetric data in kJ/g against the N content of the samples. A linear fit to the data then gives the heat of drop solution for stoichiometric GaN to determine the heat of formation through a thermochemical cycle. The same methodology was used previously to study $Si_3N_4$ and can be used in the future to study III-V alloys (InGaN, AlGaN, etc). Project to determine the heat of formation of nanocrystalline GaN is currently in progress.

**W3.64**
GaN DECOMPOSITION IN AMMONIA. D.D. Koleske, A.E. Wickenden, and R.L. Henry, Code 6861, Naval Research Laboratory, Washington, DC.

Unlike the other III-V semiconductors, the MOVPE growth of GaN occurs at temperatures well above the onset of decomposition. While GaN decomposition has been studied in $H_2$, $N_2$, and vacuum environments, few studies have focused on GaN decomposition in mixed $NH_3$ and $H_2$ flows, which is more characteristic of the MOVPE growth environment. In this presentation, GaN decomposition is measured in mixed $H_2$ and $NH_3$ flows. At 1000 °C, the GaN decomposition rate is reduced from approximately $1x10^{16}$ $cm^{-2}s^{-1}$ in pure $H_2$ to a minimum of approximately $1x10^{14}$ $cm^{-2}s^{-1}$ as $NH_3$ is added to the total flow. As the $NH_3$ density is increased above $1x10^{19}$ $cm^{-3}s^{-1}$ the GaN decomposition rate increases. The increase in the GaN decomposition rate as the $NH_3$ density increases may partly explain decreases in the GaN growth rate as the growth pressure is increased. This behavior of the GaN decomposition rate vs. pressure in mixed $NH_3$ /$H_2$ flows is similar to that in pure $H_2$ flows, suggesting a similar role of the surface hydrogen in the decomposition kinetics [1]. A model to explain the dependence of the GaN decomposition rate as a function of hydrogen coverage will be presented as well as implications for the incorporation and decomposition rates in comparison to the growth rates.
Sponsored by the Office of Naval Research.
[1] D.D. Koleske *et al.*, Appl. Phys. Lett. 73, 2018 (1998).

**W3.65**
EXPOSURE OF THE WURTZITE GALLIUM NITRIDE (0001) SURFACE TO MAGNESIUM AND ARSENIC. V. Ramachandran, R.M. Feenstra, Department of Physics, Carnegie Mellon University, Pittsburgh, PA; D.W. Greve, Department of Electrical and Computer Engineering, Carnegie Mellon University, Pittsburgh, PA; A.R. Smith, Department of Physics and Astronomy, Ohio University, Athens, OH; W.L. Sarney, L.M. Salamanca-Riba, Department of Materials and Nuclear Engineering, University of Maryland, College Park, MD; J.E. Northrup, Xerox, Palo Alto Research Center, Palo Alto, CA.

We have studied the exposure of the wurtzite GaN(0001) surface to As and Mg in order to determine their effect on molecular beam epitaxy (MBE) growth. Submonolayer quantities of Mg deposited during the growth of GaN films on SiC by MBE are seen to stabilize film growth in the Ga-poor growth regime. In the absence of Mg, GaN growth in this regime is characterized by 3-dimensional growth as evidenced by spotty reflection high-energy electron diffraction (RHEED) patterns, whereas growth in the Ga-rich regime shows streaky, 1×1 RHEED

patterns. We see that growth of Ga-polar GaN performed under Ga-poor conditions, upon exposure to < 0.2 monolayer (ML) of Mg, reverts to planar growth, clearly indicative of the surfactant effect of Mg. Deposition of approximately 1 ML of Mg on a Ga-polar film during growth inverts the polarity of the entire film. Transmission electron microscopy studies reveal an inversion boundary lying in the (0001) plane. A theoretical model for an inversion boundary in the (0001) plane incorporating Mg atoms is proposed. Arsenic exposure of the Ga-polar GaN surface during growth in highly Ga-rich conditions does not have much effect on the RHEED pattern which stays dim and streaky. However, when the Ga-flux is reduced and the conditions approach the boundary between Ga-rich and Ga-poor, a bright 2×2 RHEED pattern is seen during growth which persists upon cooling the sample. We have seen the streaky 2×2 regime to extend into nitrogen-rich growth conditions which suggests a surfactant effect of As. Under very Ga-poor conditions, the surface roughens as before. We survey this behavior of As on Ga-polar GaN for different Ga and As concentrations and discuss theoretical models for the reconstruction during growth. This work has been funded by the Office of Naval Research and the National Science Foundation.

**W3.66**
STRUCTURE OF GaN(0001)-1*1:HOLOGRAPHY STUDY OF Mg ADSORPTION ON GaN(0001) SURFACE. S.H. Xu, H. Cruguel, Y. Yang, G.J. Lapeyre, Physics Department, Montana State University, Bozeman, MT; J.F. Schetzina, Physics Department, North Carolina State University, Raleigh, NC.

A major issue concerning the properties of interfaces and the possibility to control their formation is the atomic structure of adatoms. Direct space atomic structure is obtained from angle-resolved photoemission data obtained with the synchrotron radiation. Core level emission from the atom of interest contains interference effect as a function of electron wave number (equivalent to photon energy) and emission direction. The effects can be inverted by using the holographic principle to obtain a real space image of the atoms surrounding the emitter. The data is obtained from MOVPE grown samples which are atomically clean by heating in the spectrometer. The results reveal the adsorption site of Mg on GaN(0001) surface. The experimental image shows that Mg adsorbs on the so-called $T_4$ site with one N atom directly below it. Also the image demonstrates that there is one monolayer Ga adatoms on the surface. The Ga adatoms sit on the so-called $H_3$ site with no atom directly below it. The site position results are rather complex. As a result theoretical simulation were performed and verified the assignment of the peaks in the experimental image. Research supported by ONR DEPSCoR and Wisconsin Synchrotron Radiation Center supported by NSF.

**W3.67**
AMMONIA ADSORPTION ON GaN(0001). H. Cruguel, Y. Yang, S.H. Xu, G.J. Lapeyre, Montana State University, Bozeman, MT; E. Rotenberg, Advanced Light Source, Berkeley, CA; J.F. Schetzina, North Carolina University, Raleigh, NC.

GaN has attracted much attention because of its great importance for the development of high power electronic and electro-optic devices. The in situ gas deposition of NH3 on n-GaN(0001) clean surface is investigated with photoemission. The MOCVD samples grown at N.C. State University were successfully clean, and measured at the Advanced Light Source (ALS) in Berkeley. High-resolution data are collected for the valence band VB) and both N1s and Ga3d photoemission levels for the clean surface and for sequential exposures of Ammonia at two different temperature (25°C and 600°C). The clean substrate emission for N1s has a surface component, which is about 20% in intensity and shifted by 0.86 eV to smaller binding energy than the bulk component. The Ga surface peak is shifted to larger binding energy. A wildly accepted model is that the film has Ga polarity with a Ga adlayer. The N1s shifted peak is attributed to the top N layer under the two Ga layers. The N signal saturated at about 2L of NH3 exposure which correlates with the extinguished of the VB surface state. This is attributed to one or two monolayers. The N1s level shows three new components with relative shifts of 0.92, 0.78, and 0.74 eV to larger binding energy. Their amplitudes decrease with increasing shifts. We suggest that these peaks are for different hydrogen coordination. We also found that in the early stage of the exposure, the bulk component of the N1s increases. The small increase in the component is attributed to the Ammonia exposure modify the Ga adlayer. Annealing experiments were performed and the NH3 induced effects disappear at about 850°C, with the surface essentially returning to the clean condition, with very slight differences in the N1s emission. The results will be discussed in terms of possible adsorption models. † Supported by ONR DEPSCOR

**W3.68**
IN-SITU PHOTOELECTRON SPECTROSCOPY INVESTIGATION OF THE REACTIVITY OF THE ALUMINUM NITRIDE SURFACE. T. Wrase, P. Reinke, P. Oelhafen, Universitat Basel, Institut für Physik, Basel, SWITZERLAND.

The interest in the properties of the AlN surface has been triggered by the possibility of the presence of a negative electron affinity. However, the investigation of the electronic structure is hampered by the presence of a stable oxide layer. In the current study polycrystalline AlN films are prepared by reactive magnetron sputtering in an UHV-preparation chamber, thus avoiding immediate contamination of the surface. The subsequent analysis of the samples is performed in-situ and photoelectron spectroscopy in the ultraviolet (UPS) and x-ray regime (XPS) is employed. Owing to the in-situ preparation it is, to our knowledge for the first time, possible to obtain reliable information on the electronic structure and chemical composition of the as-prepared AlN surface. The samples were prepared at different substrate temperatures (ambient to 960°C), leading to varying crystal quality. The valence band (VB) structure of the pure AlN surface is dominated by two peaks, which can be related to bands of p- and s-character, and the electron affinity is close to zero. However, some uncertainties in the determination of the electron affinity arise from the shape of the valence band. The exposure of AlN surfaces to molecular oxygen leads to a rapid accumulation of oxygen at the surface: a thin oxide layer is formed and a peak related to the oxidized Al emerges in the VB. The electron affinity increases, clearly showing the destruction of a possible negative electron affinity by exposure of AlN to air. Considerable changes in the electronic properties of the surface are initiated by firstly, the exposure to atomic hydrogen, or secondly, the growth of amorphous hydrogenated carbon film, intended to function as passivation layer. The different reactions at the AlN surface and their influence on the electron affinity and band bending will be compared and discussed in detail.

**W3.69**
EVOLUTION OF THE ELECTRONIC STRUCTURE OF GaN DURING OXIDATION. Neil J. Watkins[1], Gary W. Wicks[2], Yongli Gao[1]; [1]Dept of Physics and Astronomy, [2]The Institute of Optics, Univ of Rochester, Rochester, NY.

Previous work has shown that the oxidation of GaN(0001) is limited to the creation of surface oxides. This leads to the question of what effect does this oxidation have on the electronic structure of the surface. We examine the evolution of the electronic structure of n-type GaN(0001) during the oxidation process. Angle resolved measurements were made with inverse photoemission spectroscopy (IPES), ultraviolet photoemission spectroscopy (UPS), and x-ray photoemission spectroscopy (XPS). The evolution of the changes seen in UPS spectra that are attributed to oxygen exposure are shown relative to the degree of oxidation as measured by XPS. The combined use of IPES and UPS allows us to chart the evolution of the surface valence and conduction band positions along with the work function and electron affinity of the GaN(0001) surface during the oxidation process.

**W3.70**
HYDROGEN PASSIVATION OF EDGE DISLOCATIONS IN GALLIUM NITRIDE. Alan F. Wright, Kevin Leung, Sandia National Laboratories, Albuquerque, NM.

We have studied the atomic and electronic structure of a hydrogen-passivated edge dislocation in GaN using first-principles total-energy calculations. For stoichiometric core structures and core structures having excess nitrogen atoms, hydrogen is found to passivate nitrogen dangling bonds leaving the core structure largely unchanged and shifting defect levels toward the band edge. For core structures having excess gallium atoms, hydrogen is found to break strained Ga-N bonds leading to substantial changes in the dislocation core structure and its defect levels. Formation energies, as a function of growth conditions and Fermi level, are compared for various core structures both with and without hydrogen passivation. These energies are used to predict the likely dislocation core structures, and the corresponding defect levels are used to determine the amount of line charge accumulated at the dislocation as a function of the doping level in the surrounding material. We also give the binding energy of hydrogen at an edge dislocation and compare this value to binding energies for hydrogen at point defects in GaN.

**W3.71**
INVESTIGATIONS ON GaN SURFACE POLARITY AND InN/GaN HETEROSTRUCTURES BY COMPUTATIONAL CHEMISTRY. Takayuki Onozu, Yusaku Inaba, Seiichi Takami, Momoji Kubo, Akira Miyamoto, Tohoku Univ., Dept. of Materials Chemistry, Sendai, JAPAN; Yasushi Iyechika, Takayoshi Maeda, Sumitomo Chemical Co. Ltd., Tsukuba Research Lab., Tsukuba, JAPAN.

The heteroepitaxial growth of highly perfect GaN layers on sapphire substrates by metalorganic vapor phase epitaxy method has become possible due to the development of the GaN or AlN buffer layer

deposition technique. It is reported that the initial treatment of sapphire substrate, such as initial nitridation and low temperature GaN buffer layer deposition, affects the surface morphology and crystallinity of GaN grown layers [1]. Grown GaN planes have a polar configuration, i.e., either Ga or N can occupy the first atomic layer. The polarity of these surfaces can have important effects in semiconductor interfaces, i.e., InGaN/GaN interfaces. However, as for more relevant (0001) growth surface of the hexagonal GaN, its structure is not well known yet. In the present study, we have investigated the reconstructions and the charge states of the Ga-terminated and the N-terminated GaN surface by the periodic density functional theory (DFT) method and the effects of surface polarity of GaN on InN/GaN interface (as simple model of InGaN/GaN interface) by the molecular dynamics (MD) method [2]. The DFT calculations predicted that the reconstruction of the N-terminated GaN (0001) surface is energetically more favorable than that of the Ga-terminated surface. The MD results suggested that the growth of InN thin films on the Ga- and N-terminated surfaces is different. On the N-terminated surface, the surface morphology of the grown InN layer was three-dimensional and rough. On the other hand, on the Ga-terminated surface, it was observed that the InN molecules have adequate migration mobility for growth and this suggests that the growth follows the two-dimensional growth mode.
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[2] T. Onozu, I. Gunji, R. Miura, S.S.C. Ammal, M. Kubo, K. Teraishi, A. Miyamoto, Y. Iyechika, and T. Maeda, Jpn. J. Appl. Phys. 38 (1999) 2544.

**W3.72**
CLASSICAL SIMULATIONS OF DEFECT-INTERFACE INTERACTIONS IN GaN. James A Chisholm, Paul D. Bristowe, Dept of Materials Science and Metallurgy, Cambridge, UK.

Vacancy and interstitial native defects are known to have a major influence on the electrical and optical properties of GaN. For example, the N vacancy acts as a shallow donor, the Ga vacancy as an acceptor and the interstitials act as amphoteric defects. Formation energies for native defects in bulk GaN are well established, however these formation energies will be changed in the location of extended planar defects such as stacking mismatch boundaries and inversion domain boundaries. To date the interaction between such boundaries and native defects in GaN is not understood and it remains unclear whether the formation of interstitials and vacancies is encouraged or discouraged. We employ a classical pair potential model to calculate the binding energy of native defects to three commonly observed interfaces: $(10\bar{1}0)$ stacking mismatch boundary (SMB), $(10\bar{1}0)$ inversion domain boundary (IDB) and a $(11\bar{2}0)$ IDB. Simulations are carried out using the GULP computer code incorporating polarization effects using the shell model. Large supercells containing over 500 atoms are employed in order to eliminate intercellular interactions. Calculations on the $(10\bar{1}0)$ IDB show that both Ga and N vacancies have lower formation energies in the boundary. The binding energy to the boundary for both is calculated to be 0.4 eV. Vacancies do little to alter the structure of bulk GaN and this result also applies to the boundary where only minimal lattice relaxations are observed. The contrast between bulk and boundary formation energy is more pronounced for interstitials. Binding energies of 1.5 eV and 10.1 eV are found for the Ga and the N interstitial respectively. These high binding energies reflect the finding that, unlike in bulk, there is enough space to introduce interstitials without distorting the surrounding structure. These results are compared to those found for the $(11\bar{2}0)$ IDB and the $(10\bar{1}0)$ SMB.

**W3.73**
LATTICE LOCATIONS, DIFFUSION, AND EXTRINSIC LEVELS OF Li IN GaN. Fabio Bernardini and Vincenzo Fiorentini, INFM and Dipartimento di Fisica, Università di Cagliari, ITALY.

Ab initio density-functional calculations are presented for Li in GaN. The preferred charge state is +1 and the corresponding lattice location is in the wurtzite channel, slightly slanted towards the N atoms in the upper three-fold ring, in excellent agreement with channeling experiments. In perfect GaN, this is the only stable site for Li. By mapping its potential energy surface, we find Li diffuses into GaN (preferentially in the a-plane) above about 600 K, which also agrees well with the experimental estimates. In addition, Li recombination with Ga vacancies is highly exothermic, and is a barrier-less reaction. This is an efficient pathway to Li substitution of Ga in Ga-poor GaN. The substitutional double acceptor $Li_{Ga}$ thus realized is highly stable again interstitialcy, and has shallow first and second ionization levels of 0.18 eV and 0.32 eV, respectively. The vacancy-Li recombination occurs with the concurrent capture of one or two electrons depending on the Fermi level. Li will thus function as an efficient compensator of Ga vacancies.

**W3.74**
SCHOTTKY BARRIERS AND OTHER EFFECTS AT NITRIDE/METAL JUNCTIONS: Ti, Au, TiN, AND Cd ON $\alpha$- AND $\beta$-GaN AND AlN. Paolo Ruggerone, Fabio Bernardini, Daniele Mura, and Vincenzo Fiorentini, INFM and Dip. di Fisica, Università di Cagliari.

We investigated by first-principles density functional calculations a number of junctions of both wurtzite and zincblende GaN and AlN with several hcp (Ti, Cd), fcc (Au, Ti), and NaCl-structure (TiN) metals, considering different possible terminations and reconstructions of the (0001) and (111) surfaces. The technologically relevant result of this study are the theoretical valence Schottky barriers; we mention here the lowest and highest values, namely 0.1 eV for Au on w-GaN, and 2.2 eV for Ti on w-GaN. In this latter context our results indicate that the actual interface at a real-world Ti/GaN contact is likely to be an interface with a TiN layer, whose formation is energetically favorable. Other, more basic issues we will be reporting on, concern structure-related anomalies of the barriers, and Friedel oscillation due to the interface perturbation in some of the metals considered.

**W3.75**
COMPUTATIONAL CHEMISTRY STUDY ON CRYSTAL GROWTH PROCESS OF NITRIDE SEMICONDUCTOR. Yusaku Inaba, Takayuki Onozu, Ryuji Miura, Seiichi Takami, Momoji Kubo, Akira Miyamoto, Tohoku Univ, Dept of Materials Chemistry, Sendai, JAPAN.

The GaN is one of the candidate materials for blue light-emitting diodes and semiconductor blue lasers. But the lattice mismatch between GaN and sapphire, which is commonly used as substrates for epitaxy of nitrides, is large. Thus, buffer layers that are grown at low temperature (AlN, GaN etc) are used to obtain the epitaxtial GaN layers. In this study, we investigated the initial stage of AlN and GaN growth process on $Al_2O_3(0001)$ surface using the computational chemistry methods. We calculated the energy of the AlN and GaN small clusters from monomer to tetramer as well as their cohesive energies. The cohesive energies of AlN are lager than GaN in dimer and trimer cases. Moreover, from the optimizesd structures it can be seen that the Al-N bond is shorter and hence more cohesive than the Ga-N bond. This result suggests that at the initial stage of growth process the AlN molecules tend to aggregate each other to form stable cluster. On the other hand, the weak Ga-N bond provides a possibility of forming the GaN monolayer deposition film on $Al_2O_3$ substrate.

**W3.76**
THEORETICAL STUDY OF PHONON MODES IN AlGaN ALLOYS. Claudia Bungaro and Stefano de Gironcoli, International School for Advanced Studies (SISSA-ISAS), Trieste, ITALY.

We present a theoretical study of the vibrational properties of the (AlGa)N ternary alloys using first-principles calculations. In spite of the interest elicited by the group-III nitride ternary alloys as a result of their potential device applications, the vibrational properties of these materials are still poorly studied. We have calculated the zone-center phonon frequencies for (AlGa)N alloys in the wurtzite structure and characterized their behavior as a function of the aluminum concentration over the whole compositional range from pure GaN to pure AlN. Our findings explain well the available experimental data. The phonon modes are broadened upon alloying and their frequencies display a blue shift with increasing the aluminum concentration. Upon alloying, we find different behavior for the different optical modes. Some of the modes preserve a well-defined symmetry and display a one-mode behavior, while some have a mixed symmetry and display a two-mode behavior. From our results we can conclude that the $A_1(LO)$ and $E_1(LO)$ modes are the best candidates for the material characterization of this system as they have a well defined symetry, small broadening, and a pronounced dependence upon alloy composition. Our calculations are based upon state-of-the-art density-functional perturbation theory and the vibrational properties of the alloy are treated within the mass approximation.

**W3.77**
EFFECT OF THE DOPING AND THE Al CONTENT ON THE MICROSTRUCTURE AND MORPHOLOGY OF THIN $Al_xGa_{1-x}N$ LAYERS GROWN BY MOCVD. J.H. Mazur, M. Benamara, Z. Liliental-Weber, W. Swider, J. Washburn, E.O. Lawrence Berkeley Laboratory, Berkeley, CA; C. Eating, R.C. Dupuis, R.D. Dupuis, Microelectronics Research Center, University of Texas, Austin TX.

Several $Al_xGa_{1-x}N$ {x=30% (doped and undoped), 45% (doped)} thin films were grown by MOCVD on 2 nm thick GaN layer using $Al_2O_3$ substrate. These films were aimed to be the active part of HFETs with $n_s\mu$ product of about $10^{16}(Vs)^{-1}$. They were then studied by means of transmission electron microscopy (TEM) techniques. In this paper, it is shown that the layer thickness was non

uniform due to presence of V-shaped defects within the $Al_xGa_{1-x}N$ films. The nucleation of these V-shaped defects has taken place about 20 nm above the $Al_xGa_{1-x}N$/GaN interface. Many of these V-shaped defects were associated with the presence of the threading dislocations propagating from the GaN/$Al_2O_3$ interface. We show that the density of these V-shaped defects increases with the doping level and also with the Al mole fraction in the films. The formation mechanism of the V-shaped defects seems to be related to the concentration of dopants (or other impurities) at the ledges of the growing film. This suggestion is supported by high resolution TEM analysis. The growth front between the V-shaped defects in the lower Al concentration thin films was planar as compared with the three-dimensional growth in the doped higher Al concentration film.

**W3.78**
MAGNESIUM DOPING IN AlGaN/GaN SUPERLATTICE STRUCTURES. Hyeongsoo Park, Jin-Seok Kim, Ok-Hyun Nam, Cheolsoo Sone, Bongjin Kim, Yongjo Park, Taeil Kim, Photonics Lab., Samsung Advanced Institute of Technology, Suwon, KOREA.

For various electronic and optoelectronic device applications, how to grow p-type GaN and AlGaN layers having high hole concentration is still remaining issue. To get a good optical confinement, high Al content in the AlGaN cladding layer of the GaN LDs is necessary. However this causes the difficulties of p-type doping and the cracking problem due to highly strained heterointerfaces when using the bulk AlGaN cladding layer. A few results on this issue have been reported So far. Nakamura et al. used modulation doped AlGaN/GaN superlattices as the cladding layer in violet laser diode. Very recently, Kozodoy et al. reported the effect of enhanced Mg-doping efficiency of AlGaN/GaN superlattices. In this study, high p-type conductivity of Mg-doped AlGaN/GaN superlattices was achieved by low-pressure organometallic vapor phase epitaxy. The dependence of hole concentration on the thickness of both the well and the barrier in the superlattices and the modulation doping effect were studied. The measured hole concentration at room temperature is about 3.9E18 $cm^{-3}$ and lateral resistivity was as low as 0.23 ohm-cm. The mobility of this superlattice structures was increased as the thickness of the well and barrier was increased. Additional results will be reported at the conference.

**W3.79**
EFFECTS OF IMPLANTATION FLUENCE AND TEMPERATURE ON DOPANT ACTIVATION AND DAMAGE RECOVERY IN EPITAXIAL GaN CHARACTERIZED BY PL AND SEM. Agajan Suvkhanov, N. Parikh, and I. Usov, Dept. of Physics and Astronomy, U. of North Carolina, Chapel Hill, NC; J. Hunn and S. Withrow, Oak Ridge National Lab, Oak Ridge, TN; D.Thomson, R.F. Davis, Dept. of Mat. Sci. and Eng., NC State University, Raleigh, NC; L. Ya. Krasnobaev, Implant Sciences, Corp., Wakefield, MA.

Epitaxial GaN films deposited on 6H-SiC were implanted with 100 keV Si+ and 80 keV Mg+ at 77 K, 823 K and 973 K of fluences ranging from 1e12 to 7x1e15 $cm^{-2}$. All as-implanted samples were capped with 40 nm of AlN films to protect GaN from degradation during high temperature annealing of implantation damage. Photoluminescence spectra of as-deposited GaN with AlN capped and uncapped samples were almost identical, indicating AlN capping did not affect PL measurements. Implanted samples were annealed in conventional furnace at 1573 K after placing them face-to-face in quartz tube and encapsulating under high purity over pressure of nitrogen. Optical and structural characterization of as-implanted and annealed samples were carried out using low temperature PL, Rutherford backscattering/Channeling (RBS/C), Spectroscopic Ellipsometry (SE) and Scanning Electron Microscopy (SEM) techniques. PL studies of as-implanted samples showed an increase in yellow luminescence (peaked around 2.23 eV) with implantation fluence which is associated with implantation damage. Initial results of samples implanted at 823 K showed systematic reduction in the yellow luminescence and increase in band edge luminescence with the decrease in implantation fluence. The full width half maximum (FWHM) of the yellow luminescence peak decreased for a given fluence with increase of implantation temperature. However, for a given implantation temperature a variation in FWHM of the yellow luminescence peak was not significant. Detailed characterization of annealed samples is underway to understand the influence of implant fluences and temperature on dopant activation and damage annealing. * Research sponsored by the Division of Materials Sciences, U.S. Department of Energy under contract number DE-AC05-96OR22464 with Lockheed Martin Energy Research Corporation.

**W3.80**
ELECTRICAL AND OPTICAL PROPERTIES OF OXYGEN DOPED GaN GROWN BY MOVPE. R.Y. Korotkov and B.W. Wessels Materials Research Center and Department of Materials Science and Engineering, Northwestern University, Evanston, IL.

The identity of the shallow donor in epitaxial GaN still is under investigation. Oxygen is considered a possible candidate to explain the high conductivity of unintentionally doped layers. In this study oxygen doped GaN has been grown by metalorganic vapor phase epitaxy using an oxygen-nitrogen mixture as the dopant source. The doped layers were n-type with carrier concentrations in the range of $1\times10^{17}$ to $4\times10^{19}$ $cm^{-3}$. The observed carrier concentration had a sublinear dependence on oxygen partial pressure. Photoluminescence was used to characterize the shallow donors and acceptors in the doped films. In addition to free donor and acceptor bound exciton emission bands, a new broad band located at 3.56 eV with an asymmetrical line shape was observed. The dependence of the emission intensity of the 3.56 eV band on oxygen concentration was examined.

**W3.81**
OPTICAL AND ELECTRICAL PROPERTIES OF MBE GROWN CUBIC GaN/GaAs EPILAYERS DOPED BY Si. D.J. As, A. Richter, J. Busch, B. Schöttker, M. Lübbers, J. Mimkes, D. Schikora, and K. Lischka, Universität Paderborn, FB-6 Physik, Paderbon, GERMANY.

The optical and electrical properties of n-type doping with Si in cubic GaN (c-GaN) epilayers are reported. Cubic GaN films are grown by rf-plasma assisted MBE on semi-insulating GaAs (001) substrates at a substrate temperature of 720°C, a growth rate of about 0.07$\mu$m/h and a layer thickness of about 1$\mu$m, respectively. Elemental Si is evaporated from commercial available effusions cells with varying Si-fluxes ranging from $10^6$ to $5*10^{11}$ atoms/$cm^2$s. Low temperature photoluminescence (PL) and temperature dependent Hall-effect measurements are used to study the optical and electrical properties. At 2 K the spectrum of the sample grown with the lowest Si-flux ($8.5*10^5 cm^{-2}s^{-1}$) is dominated by an excitonic transition X at 3.26 eV and an omnipresent donor-acceptor pair transition (D°,A°) at 3.15 eV. With increasing Si flux a clear shift of the (D°,A°) emission to higher energies and an increase of its linewidth is observed. For samples with a Si-flux exceeding $1*10^{11} cm^{-2}s^{-1}$ both lines merge to one broad band. This behavior is similar to the one observed in the case of GaAs heavily doped with Si or Te and will be dicussed in view of electron-impurity interactions (band tailing), shrinkage of the band gap due to exchange interaction between free carriers and conduction band filling effects. The influence of the high dislocation density ($\approx 10^{10} cm^{-2}$) on the electrical properties of c-GaN is reflected in the dependence of the electron mobility on the free carrier concentration. Similare to hexagonal GaN the mobility first increases with carrier concentration, reaches a maximum value of about 100 $cm^2$/Vs at an electron concentrations of about $3*10^{19}$ $cm^{-3}$ and decreases at higher electron concentrations again. This behavior is characteristic for the influence of dislocation scattering, and shows that also in cubic GaN threading edge dislocations are electrically active.

**W3.82**
ACTIVATION OF Be-IMPLANTED GaN BY TWO-STEPS ANNEALING. Yuejun Sun, Leng Seow Tan, Soo Jin Chua, Natioanl Univ of Singapore, Dept of Electrical Engineering, Center for Optoelectronics, SINGAPORE.

A new annealing process was carried out for the beryllium implanted gallium nitride. The implanted samples were annealed in ambience of forming gas including 20% $H_2$ at first and then in pure $N_2$ atmosphere. The activation of Be as acceptor was observed by the evidence from Hall measurements and photoluminescence (PL) measurements. The line in the room-temperature PL spectra at 3.36 eV was thought as band-acceptor (eA) recombinations. The optical activation energy of 90±10 meV was estimated, confirming Be as the most shallow acceptor in GaN.

**W3.83**
THE INFLUENCE OF DOPANTS AND SUBSTRATE MATERIAL ON THE FORMATION OF Ga VACANCIES IN EPITAXIAL GaN LAYERS. J. Oila, V. Ranki, K. Saarinen, P. Hautojarvi, Laboratory of Physics, Helsinki University of Technology, FINLAND; J. Likonen, Technical Research Centre of Finland, FINLAND; J.M. Baranowski, K. Pakula, Institute of Experimental Physics, University of Warsaw, POLAND; M. Leszczynski, I. Grzegory, UNIPRESS, High Pressure Research Center, Polish Academy of Sciences, POLAND.

Epitaxial GaN layers grown by MOCVD were studied using a low-energy positron beam and secondary ion mass spectrometry. Positron experiments reveal high concentrations of Ga vacancies in nominally undoped GaN grown on sapphire. These layers show n-type conductivity due to unintentional oxygen incorporation. Ga vacancies are detected also in homoepitaxially grown n-type layer on bulk GaN:Mg and in lattice matched heavily n-type layer grown on $NdGaO_3$. Only very low Ga vacancy concentrations are observed in samples, where the n-type doping is done with Si impurities and the amount of residual oxygen is reduced. No Ga vacancies are detected in p-type or semi-insulating samples doped with Mg. The formation of Ga vacancies seems to be independent of the dislocation density

because they are found even in homoepitaxial material, where the dislocation concentration is greatly reduced compared to layers grown on sapphire. The Ga vacancies are observed only in n-type samples which contain oxygen and much less Ga vacancies are formed when the n-type conductivity is due to Si doping. This indicates that the presence of oxygen donor in GaN promotes the formation of Ga vacancy. We suggest that this effect is due to the creation of $V_{Ga} - O_N$ complexes. These results are in good agreement with theoretical calculations [1,2], which predict that the formation energy of Ga vacancies is high in p-type and in semi-insulating GaN, but greatly reduced in n-type material, and in presence of oxygen even further reduced due to the formation of $V_{Ga} - O_N$ complexes. [1] J. Neugebauer and C.G. Van de Walle, Appl. Phys. Lett. 69, 503 (1996). [2] T. Mattila and R.M. Nieminen, Phys. Rev. B 55, 9571 (1997).

**W3.84**
CO-DOPING CHARACTERISTICS OF Si AND Zn WITH Mg IN P-TYPE GaN. K.S. Kim, C.S. Oh, J.-H Kim, K.J. Lee, G.M. Yang, J.W. Yang, C.-H Hong, K.Y. Lim, and H.J. Lee, Dept. of Semiconductor Science and Technology, Semiconductor Physics Research Center, Chonbuk National University, S. KOREA.

The realization of high conducting p-type GaN film is one of the key factors to the success of GaN based light emitters with low series resistance. Mg has been accepted as a typical acceptor dopant in GaN, known to have the smallest ionization energy compared with other acceptor dopant sources, namey Zn, Be, etc. Nevertheless, it is difficult to obtain the p-type GaN with low resistivity and high hole concentration because it is still deep from the valence band maximum. However, in recent, it was theoretically suggested that co-doping of n-type dopants (Si, O, etc.) together with p-type dopants (Mg, Be, etc.) in GaN is effective for the fabrication of high-conductivity p-type GaN. It drives us to the study of co-doping characteristics in metalorganic chemical vapor deposition grown p-type GaN. In this work, we have studied the co-doping characteristics of Si with Mg as well as Zn with Mg. For the case of co-doping of Si with Mg, the hole concentrations are interestingly increased as $SiH_4$ flow rates increase, and then type conversion arises at the $SiH_4$ flow rate of 0.13 nmol/min. This dependence can be effectively explained by taking advantage of the concept of competitive adsorption between Si and Mg during the growth, which is also corroborated by low temperature photoluminescence spectroscopy. Theoretically, the co-doping of two different p-type dopants in GaN is not helpful to get a high conducting p-type GaN, because it forms a lot of native defect levels leading to hole compensation. However, it was observed that the co-doped p-type GaN of Zn with Mg show relatively low resistivity and high hole concentration compared with only Mg doped p-type GaN. The specific contact resistivity measured from transmission line method with ring contact geometry shows lower value by almost one order of magnitude for Zn with Mg co-doped GaN than that of only Mg doped GaN layers. Therefore, the co-doped GaN layer of Zn with Mg is expected to act as a good contact layer.

**W3.85**
EFFICIENT ACCEPTOR ACTIVATION IN $Al_xGa_{1-x}N$/GaN DOPED SUPERLATTICES. I.D. Goepfert and E.F. Schubert, Dept of Electrical and Computer Engineering, Boston University, Boston, MA; A. Osinsky and P.E. Norris, NZ Applied Technologies, Woburn, MA.

Mg-doped superlattices consisting of uniformly doped $Al_xGa_{1-x}N$ and GaN layers are analyzed by Hall-effect measurements. Acceptor activation energies of 70 meV and 58 meV are obtained for superlattice structures with an Al mole fraction of x = 0.10 and 0.20 in the barrier layers, respectively. These energies are significantly lower than the activation energy measured for Mg-doped bulk GaN. At room temperature, the doped superlattices have free hole concentrations of $2*10^{18}$ $cm^{-3}$ and $4*10^{18}$ $cm^{-3}$ for x = 0.10 and 0.20, respectively. The increase in hole concentration with Al content of the superlattice is consistent with theory. The room temperature conductivity measured for the superlattice structures are 0.27 S/cm and 0.64 S/cm for an Al mole fraction of x = 0.10 and 0.20, respectively.

**W3.86**
STUDIES OF Si-DOPING OF AlN GROWTH BY PSMBE. Feng Zhong, Wayne State University, Dept of Chemical Engineering and Materials Science, Detroit, MI; Changhe Huan, Gregory W. Auner, Wayne State University, Dept of Eelectrical and Computer Engineering, Detroit, MI.

As-grown AlN by Plasma Source Molecular Beam Epitaxy (PSMBE) is usually an insulator with sheet resistance values greater than $10^{13}\Omega$·cm. AlN is difficult to dope due to its wide bandgap and high ionic bonding. This seriously limits the application of AlN as a semiconductor. Thus useful doping of AlN must be solved first in order to explore the full potential application of AlN. Experimental studies of Si-doping of AlN are investigated. Si doping is achieved concurrently with epitaxial AlN thin film depositing by Plasma Source Molecular Beam Epitaxy. Two Silicon sources (solid Silicon PSMBE source and gaseous Silane source) are used. The resistivities, carrier concentrations and mobilities of thin films are measured by four-point probe and Hall effect measurement, respectively. The impurity state and doping concentration profile is characterized by Cathodluminescence and SIMS, respectively. The effects of Silicon flux as a function of electrical properties are presented.

**W3.87**
STRUCTURAL AND OPTICAL PROPERTY INVESTIGATIONS ON MG-DOPING IN EPITAXIAL ZINC OXIDE FILMS ON SAPPHIRE. A.K. Sharma, C. Jin, J. Narayan, North Carolina State University, Department of Materials Science and Engineering, Raleigh, NC; C.W. Teng, J.F. Muth, R.M. Kolbas, North Carolina State University, Department of Electrical and Computer Engineering, Raleigh, NC; O.W. Holland, Oak Ridge National Laboratory, Solid State Division, Oak Ridge, TN.

We have performed investigations on the structure and optical property correlations on the effect of Mg-alloying with Zinc oxide films. Zinc oxide[1,2] has potential applications in futuristic blue laser diodes, UV lasers, and UV detectors. In this work, we have explored the possibility of its bandgap engineering as a result of alloying with Mg for the above applications. Pulsed laser ablation of sintered compound targets made of a mixture of ZnO and MgO powders in several different ratios was employed to incorporate Mg into the ZnO films. We were able to incorporate Mg upto 30 at% which exceeds the equilibrium concentration by several orders of magnitude. High resolution microscopy of these specimens indicated epitaxial single crystal nature of the films with low defect contents. The x-ray diffraction studies showed the films to be high quality epitaxial. The phase separation of MgO could be observed at high concentrations (>30 at%) of Mg in the films by X-ray diffraction. Transmission optical spectra of these specimens exhibited sharp band-edge with the bandgap ~4 eV for the sample containing about 30 at% Mg. These specimens luminesced bright in UV with the luminescence peak widths being sharp (FWHMs ~100 meV). A comparative study of the structure, defect content and optical properties has been carried out between Mg-doped and undoped[1,2] high quality epitaxial single crystal ZnO films.
[1]J. Narayan, K. Dovidenko, A.K. Sharma, and S. Oktyabrsky, J. Appl. Phys., 84, 2597 (1998).
[2]J.F. Muth, R.M. Kolbas, A.K. Sharma, S. Oktyabrsky, and J. Narayan, J. Appl. Phys., 85, 7884 (1999).

**W3.88**
NITRIDE DEVICES ON LATTICE-MATCHED ZINCE OXIDE (ZnO) SUBSTRATES. Jeffrey E. Nause, Cermet, Inc., Atlanta, GA; Hadis Morkoc, Virginia Commonwealth University, Richmond, VA.

Single crystal zinc oxide (ZnO) is a potentially valuable material for the fabrication of many nitride-based light emitters, detectors, and power devices. The properties that make zinc oxide attractive are; 1) zinc oxide has the same atomic space group as gallium nitride ($P6_3mc$), 2) zinc oxide has only a 2.2% lattice mismatch to gallium nitride, 3) zinc oxide is an electrically conductive substrate, and 4) zinc oxide is optically transparent. For light emitting applications, a lattice-matched, conductive substrate offers vertical device fabrication, which can currently only be achieved with conducting zinc oxide. For power devices, the identical atomic space group could eliminate stacking mismatch boundaries (SMBs). In all device types, the close lattice match between ZnO and GaN should greatly reduce dislocations introduced by the substrate. In this work, the ZnO bulk crystallization process will be described. Additionally, the ZnO crystal quality will described based on optical, structural, and electrical analysis. The fabrication of an aluminum gallium nitride/gallium nitride field effect transistor on ZnO, using molecular beam epitaxy, will be discussed. The defect levels in the nitride films will be analyzed using electron microscopy. The electrical properties of the nitride films will also be discussed.

**W3.89**
DOPING DEPENDENCE OF THE THERMAL CONDUCTIVITY OF HYDRIDE VAPOR PHASE EPITAXY GROWN $n$-GaN/SAPPHIRE (0001) USING A SCANNING THERMAL MICROSCOPE. D.I. Florescu, V.M. Asnin, Fred H. Pollak, Brooklyn College, Physics Dept., Brooklyn, NY; and R. Molnar, MIT Lincoln Laboratory, Lexington, MA.

We report the first measurement of the thermal conductivity ($\kappa$) of GaN as a function of doping concentration. $\kappa$ at 300K of two series of $n$-GaN samples, fabricated by hydride vapor phase epitaxy (HVPE) on sapphire (0001) substrates, was determined using a ThermoMicroscope's scanning thermal microscope [1], which has a spatial resolution of $\approx$ 1 $\mu$m. The doping levels were from 300K Hall effect measurements. In both sets of samples $\kappa$ decreased linearly with

log $n$, a factor of two decrease in $\kappa$ for every decade increase in $n$. We found $\kappa \approx 1.95$ W/cm-K for the most lightly doped sample ($\approx 6x10^{16}$ $cm^{-3}$), higher than the previously reported $\kappa \approx$ 1.7-1.8 W/cm-K on LEO material [1] and $\approx$1.3 W/cm-K on a HVPE sample [2]. One set of samples had unintentional $n$ and thicknesses ($t$) in the range of 6-800x$10^{16}$ $cm^{-3}$ and 5-74 $\mu$m, respectively. For the second set $t$ was held constant $\approx$10 $\mu$m and 15x$10^{16}$ $cm^{-3} < n <$ 300x$10^{16}$ $cm^{-3}$. Our observation also helps to explain $\kappa$ of the LEO material, with $n$ $\approx$(1-2)x$10^{17}$ $cm^{-3}$ [3]. $\kappa$ ($n$) is similar to that of other semiconductors in a comparable temperature range [4]. The decrease in the lattice component of $\kappa$ due to increased phonon scattering (impurities and free electrons) outweighs the increase in the electronic $\kappa$. The implications of these findings for device applications and design will be discussed.

[1] V.M. Asnin *et al*, APL **75**, 1240 (1999).
[2] E.K. Sichel and J.I. Pankove, J. Phys. Chem. Solids **38**, 330 (1977).
[3] M. Pophristic et al, APL **74**, 3519 (1999).
[4] *Thermal Conduction in Semiconductors* by C.M. Bhandari and D.M. Rowe (Wiley, New York, 1988).

The Brooklyn College work was supported by the ONR and the NY State Science and Technology Foundation. The Lincoln Laboratory work was sponsored by the US Air Force under Air Force contract #F19628-95-C-002. Opinions, interpretations, conclusions, and recommendations are those of the authors and are not necessarily endorsed by the US Air Force.

**W3.90**
HIGH TEMPERATURE HARDNESS OF BULK SINGLE CRYSTAL GALLIUM NITRIDE. Ichiro Yonenaga, Tetsuya Hoshi, Institute for Materials Research, Tohoku University, Sendai, JAPAN; Akira Usui, Opto-electronics and High Frequency Device Research Laboratories, NEC Corp., Tsukuba, JAPAN

The hardness of single crystal gallium nitride at elevated temperature is measured for the first time and compared with other semiconductors. Crack-free GaN single crystals of 0.5mm thickness were obtained from a GaN layer grown on a sapphire substrate using HVPE and ELO. The grown-in dislocation density was about 107cm-2. A Vickers indentation method was used to determine the hardness under an applied load of 0.5N in the temperature range 20 - 1200°C. The average hardness of (0001) surfaces is about 10.8 GPa at room temperature, which is comparable to that of Si. The hardness of GaN shows a gradual decrease from RT to 500°C, then something of a plateau in the range 500-1000°C and then a steep decrease. Such a temperature dependent tendency is similar to that of 6H-SiC. In the whole temperature range GaN is harder than GaAs. On the other hand, the hardness of GaN is comparable to that of Si at temperatures lower than 600°C. Surprisingly, up to about 1100°C, GaN maintains its hardness and is harder than Si. Indeed, Si shows a steep decrease in hardness from 500°C with increasing temperature, due to the beginning of macroscopic dislocation motion and plastic deformation. Thus, the present results imply that such macroscopic dislocation motion and plastic deformation may start at around 1100°C on GaN and that GaN has a smaller susceptibility to deformation during device processing at high temperatures as compared with Si, GaAs, and possibly other III V compounds.

## SESSION W4: ELECTRONIC TRANSPORT AND DEVICES
Chair: John C. Zolper
Tuesday Morning, November 30, 1999
Room 302 (H)

**8:30 AM *W4.1**
AlGaN/GaN MICROWAVE TRANSISTORS. Lester F. Eastman, Cornell University, Dept. of Electrical Engineering, Ithaca, NY.

AlGaN/GaN MICROWAVE TRANSISTORS GaN has high electric field strength (3MV/cm) and good electron transport properties. Pseudomorphically strained thin $Al_xGa_{1-x}N$ grown on the Ga-face of GaN has a large combined spontaneous polarization difference and piezoelectric polarization. Undoped structures yielding a positive polarization charge of 5.5 x $10^{13}$/$cm^2$ times X, and the polarization induced two-dimensional electron gas is nearly as large. OMVPE and MBE are used to grow $\sim$300 Å of $Al_{.3}$ $Ga_{.7}$ on 1 $\mu$m of GaN on either sapphire or semi-insulating SiC yielded $\sim$ 1 x $10^{13}$/$cm^2$ 2DEG with 1200-1600 $cm^2$/V-s mobility. Ohmic contacts are formed using Ti/Al/Ti/Au annealed at 800°C for 30 seconds, and Ni/Au Schottky gates are fabricated using tri-level electron beam resist. These field-effect devices have maximum normalized channel current $\geq$ 1A/mm. Their frequency response depends reciprocally on the effective gate length, with .2 $\mu$m gates having an intrinsic cut off frequency of $\sim$ 94 GHz. Their drain-source breakdown voltage depends linearly on the effective gate length, with .5 $\mu$m gates having a 100 V limit. Devices perform well for channel temperatures up to at least 250°C. On sapphire, single 150 $\mu$m gate devices have 3.9 W/mm at 4 GHz at 36% power-added efficiency and 3.2 W/mm at 48% power-added efficiency. Devices with 12 gate fingers, each 125 $\mu$m long, had 1.8 W/mm microwave output at 4 GHz, with 78% power-added efficiency. Using semi-insulating SiC substrates, approximately ten times as much power is expected, and results on these devices will be reported and compared with GaAs devices. This MURI research is supported by ONR contract N00014-96-1-1223, and involves the efforts of 10 people working with Prof. J.R. Shealy, Dr. W. J. Schaff, and the author.

**9:00 AM *W4.2**
ADVANCES IN THE AlGaN/GaN ELECTRONICS.
Umesh K. Mishra, ECE Department, UCSB, Santa Barbara, CA.

This presentation will summarize the progress made in GaN-based materials for the Electronic applications. AlGaN/GaN HEMTs grown on Sapphire have demonstrated 4.6W/mm at 6GHz and over 7.1 W/mm when grown on SiC. Total power of 9.1W has been measured at 10GHz from AlGaN/GaN HEMTs on SiC substrates and 7.8 W from devices on Sapphire substrates. The maximum efficiency on SiC based HEMTs has been 62% (at 3.2W/mm) at 10GHz and 58% (at 4W/mm) at 6GHz for Sapphire-based devices. For power switching applications AlGaN/GaN HEMTs with over 570V breakdown has now been achieved. AlGaN/GaN HBTs have also been fabricated with a common emitter current gain at 300K of $\sim$3. All of the above performance has been achieved on dislocated epitaxial materials. With the advent of Lateral Epitaxial Overgrowth (LEO) , near dislocation free materials are now possible. The major impact of this innovation has been in the availability of CW blue lasers with a threshold current density of 1.5kA/$cm^2$. Future applications will be minority carrier devices where leakage and recombination time is important such as UV detectors and HBTs. Predictions will be made of the potential of these devices.

**9:30 AM W4.3**
POLARIZATION-INDUCED CHARGE AND ELECTRON MOBILITY IN ALGAN/GAN HETEROSTRUCTURES GROWN BY PLASMA-ASSISTED MOLECULAR BEAM EPITAXY.
I.P. Smorchkova, C.R. Elsass, J.P. Ibbetson, R. Vetury, B. Heying, P. Fini, E. Haus, S.P. DenBaars, J.S. Speck and U.K. Mishra, College of Engineering, University of California, Santa Barbara, CA.

We have performed a careful experimental study of the two-dimensional electron gases (2DEGs) formed in nominally undoped AlGaN/GaN heterostructures grown by radio-frequency plasma-assisted MBE on GaN templates deposited by MOCVD on (0001) sapphire substrates. Low-temperature electrical transport measurements revealed that the 2DEG density strongly depends on both the thickness of the AlGaN layer and alloy composition. The experimental results agree very well with the theoretical estimates of the polarization-induced 2DEG concentrations. The formation of the 2D electron channel occurs starting at a certain barrier thickness ($\sim$ 3 nm in the case of $Al_{0.27}Ga_{0.73}N$/GaN structure), determined by the energy position of the surface donor-like states which serve as a source of both 2DEG electrons and positive surface charges. Further increase of the barrier width leads to an increase in the number of the 2D electrons and its subsequent saturation at a value close to the value of the polarization-induced charge density in the AlGaN layer. The increase of the Al content in the AlGaN barrier results in an approximately linear change in the 2DEG density at a rate of $dN_S/dx$ = 5.45 x $10^{13}$ $cm^{-2}$ ($0.09 \leq x \leq 0.31$) which is consistent with the theoretical predictions and previously reported data. The low-temperature electron mobility of the AlGaN/GaN heterostructures is shown to gradually decrease with an increase in both Al mole fraction and thickness of the AlGaN barrier. These experimental results may be related to the change in the alloy disorder scattering or interface roughness scattering that significantly intensify as the density of the 2DEG increases. The established dependence of the 2DEG mobility on AlGaN barrier composition and its width has been used to achieve a low-temperature mobility of 51,700 $cm^2$/Vs (T = 13 K) in the $Al_{0.09}Ga_{0.91}N$/GaN structure with a 16 nm AlGaN barrier.

**9:45 AM W4.4**
AlGaN/GaN HEMT STRUCTURE DESIGN AND EFFECTS ON ELECTRICAL PROPERTIES. E.L. Piner, D.M. Keogh, J.S. Flynn, and J.M. Redwing, Epitronics Corp, Phoenix, AZ.

The AlGaN/GaN heterostructure system has recently been the focus of extensive research as a promising new material for microwave power devices. Pseudomorphic AlGaN layers on GaN produce a two-dimensional electron gas at the AlGaN/GaN interface resulting in high sheet carrier densities and mobilities in nominally undoped material due to polarization effects. Further increases in the sheet carrier density can be realized by modifying the HEMT structure to

include doped layers in the AlGaN barrier and/or the GaN channel. We have investigated the effects of composition, layer thickness and intentional doping on the electrical properties of AlGaN/GaN heterostructures grown by MOVPE on sapphire and SiC substrates. Both the sheet density and electron mobility were observed to increase with increasing Al composition in undoped 230Å AlGaN/GaN heterostructures. High sheet densities (>9E12 $cm^{-2}$) and mobilities (>1400 $cm^2$/Vs) were measured at room temperature in undoped heterostructures with Al compositions greater than 20%. Intentional Si doping of the AlGaN donor layer was used to further increase the sheet density at a fixed Al composition but piezoelectric-induced doping continued to dominate the carrier density in these heterostructures. Furthermore, a significant reduction in mobility (1450 to 1190$cm^2$/Vs) was observed when intentional Si dopants were added to the structure. The reduction in mobility was independent of the level of Si doping (5E17 to 5E18$cm^{-3}$) or the thickness (30 to 100Å) of the undoped spacer layer. Scattering mechanisms responsible for this effect and the implications of these results on HEMT structure design will be discussed.

**10:30 AM W4.5**
NEGATIVE DIFFERENTIAL CONDUCTIVITY IN AlGaN/GaN HEMTS: REAL SPACE CHARGE TRANSFER FROM 2D TO 3D GaN STATES? J. Deng, R. Gaska, M.S. Shur, CIEEM and ECSE, Rensselaer Polytechnic Institute, Troy, NY; M.A. Khan, J.W. Yang,Department of ECE, University of South Carolina, Columbia, SC.

We report on non-thermal negative differential conductivity (NDC) in AlGaN/GaN HEMTs grown on sapphire substrates by low-pressure MOCVD. The sheet electron density was on the order of few times $10^{12}cm^{-2}$ and the Hall mobility was 1,000 $cm^2$/V.s. The HEMTs had threshold voltage close to zero and could operate at high positive gate bias up to 3-3.5 Volts, with a very low gate leakage current. NDC was observed at the gate bias larger than 1.5V and at the drain biases between 0.5Vg and Vg. We excluded the possibility of self-heating as the cause, since the NDC occurs at relatively small power levels where self-heating effects are not important. An explanation we provided for the NDC effect is the new mechanism of real space charge transfer from 2D to 3D GaN states, which leads to a decrease in the channel mobility at large 2D electron gas densities. The observed low leakage can be explained by an enhanced molar fraction of aluminum at the heterointerface that leads to a larger conduction band discontinuity. Our model that accounts the piezoelectric and pyroelectric effects is consistent with the observed NDC effect. The real space transfer is also confirmed by low field Hall mobility data [1]. This NDC effect in GaN/AlGaN HEMTs may find applications in high-performance digital circuits at elevated temperatures. [1] R. Gaska, M.S. Shur, A.D. Bykhovski, A.O. Orlov, and G.L. Snider, Electron Mobility in Modulation Doped AlGaN-GaN Heterostructures, Appl. Phys. Lett. 74, No. 2, January 11, pp. 287-289(1999)

**10:45 AM W4.6**
AlGaN-GaN-AlGaN INDUCED BASE TRANSISTOR. Alexei D. Bykhovski, Michael S. Shur, Department of ECSE, Rensselaer Polytechnic Institute, Troy, NY; Remis Gaska, Sensor Electronic Technology, Inc., Troy, NY; M. Asif Khan, Jingwei W. Yang, Department of ECE, University of South Carolina, Columbia, SC.

We analyze the epilayer structure and characteristics of the AlGaN-GaN-AlGaN induced base transistor (IBT) that uses the two-dimensional electron gas induced into base by the piezoelectric and pyroelectric charges and by grading the emitter layer. Our calculations are based on the analytical self-consistent solution of the Poisson and Schrödinger equations at the heterointerface and on the calculations of the spontaneous and piezoelectric polarizations as functions of the lattice mismatch based on the theory of elasticity. We show that the piezoelectric and pyroelectric polarization of GaN should allow us to obtain a very low base spreading resistance, which is smaller than that for comparable GaAs- based structures. We will present the results of our calculations of the band structure and induced carrier sheet density as functions of the base width, the aluminum molar fraction profile, the doping profile, and the collector-emitter separation. We also provide a detailed comparison of these devices with more conventional bipolar transistors. Higher conduction band discontinuities should allow us to drastically reduce a leakage current. We conclude that an AlGaN-GaN-AlGaN IBT is a potential competitor to a GaN-based HBT.

**11:00 AM W4.7**
TWO-DIMENSIONAL ELECTRON GAS TRANSPORT PROPERTIES IN AlGaN/(In)GaN/AlGaN DOUBLE-HETEROSTRUCTURE FIELD EFFECT TRANSISTORS. Narihiko Maeda, Tadashi Saitoh, Kotaro Tsubaki, Toshio Nishida, Naoki Kobayashi, NTT Basic Research Laboratories, Physical Science Laboratory, Kanagawa, JAPAN.

A novel electron transport phenomenon specific to nitride heterostructures has been observed that the two-dimensional electron gas (2DEG) mobility is largely enhanced in the AlGaN/(In)GaN/AlGaN double-heterostructure (DH), compared with that in the conventional AlGaN/GaN single-heterostructure (SH). The electrical properties in the DH field effect transistor (DH-FET) have been examined, and its device operation has been demonstrated. The GaN SH-, GaN DH-, and InGaN (In=0.06) DH-FET samples were grown by metalorganic vapor-phase epitaxy (MOVPE) on SiC substrates using AlN buffer layers. The AlGaN (Al=0.15) barrier layer on the surface-side (300 Å) was uniformly doped with Si for supplying carriers. The thickness of the DH channel was 200 Å. A drastic enhancement in the 2DEG mobility was observed in the DH-FET sample. At 20 K, the 2DEG mobility in the GaN DH-FET sample exhibited a high value of 9000 $cm^2$/Vs (for a 2DEG density of $6.5\times10^{12}$ $cm^{-2}$), which was almost twice as large as the mobility in the GaN SH-FET sample. At room temperature, the 2DEG mobilities in the GaN DH- and SH-FET samples were 1020 ($8.2\times10^{12}$ $cm^{-2}$) and 710 $cm^2$/Vs ($9.4\times10^{12}$ $cm^{-2}$), respectively. The observed mobility enhancement results from the piezoelectrically enhanced electron confinement in the DH channel. Device operation of a GaN DH-FET was demonstrated: a maximum transconductance of 180 mS/mm was obtained for a 0.4-$\mu$m-gate-length device. In the InGaN DH-FET sample, an increase in the capacity for 2DEG was also observed as the result of the enhanced piezoelectric effect and the enlarged conduction-band discontinuity. At 300 K, a high 2DEG mobility of 850 $cm^2$/Vs was obtained for a very high 2DEG density of $1.9\times10^{12}$ $cm^{-2}$. The (In)GaN DH-FETs are thus promising for FET applications because of their superior electron transport properties over those in the conventional GaN SH-FETs.

**11:15 AM W4.8**
HIGH TEMPERATURE RELIABILITY OF GaN ELECTRONIC DEVICES. Seikoh Yoshida and Joe Suzuki, Yokohama R&D Laboratories, The Furukawa Electric Co., Ltd., Yokohama, JAPAN.

III-V nitrides are very promising for electronic devices that can operate under high-temperature, high-power, and high-frequency conditions, since these materials have a wide bandgap, a high breakdown electric field, and a high saturation velocity. In this paper we discuss high temperature devices using a GaN. High-quality GaN was grown using gas-source molecular-beam epitaxy (GSMBE). A GaN buffer layer was formed on the sapphire substrate using dimethylhidrazine (DMHy) and Ga. A thick undoped GaN layer was also grown on the GaN buffer layer using Ga and ammonia ($NH_3$) as a nitrogen gas source at 850°C to obtain a high-quality GaN active layer. The mobility of undoped GaN was 350 $cm^2$/Vsec and the carrier concentration was $6x10^{16}$ $cm^3$ at room temperature.
A GaN metal semiconductor field-effect transistor (MESFET) and an n-p-n GaN bipolar junction transistors (BJT) were fabricated for a high temperature operation. The aging performance of the BJT at 300°C was examined during continuous current injection at 300°C for 300 h. The BJT performance did not change at 300°C. The current gain was about 10. The BJT performance at 300°C did not changed. The high-temperature reliability of the GaN MESFET was also investigated. That is, the lifetime of the FET at 400°C was examined by continuous current injection at 400°C. We confirmed that the FET performance did not change at 400°C for over 1000 h. No degradation of the metal-semiconductor interface was observed by secondary ion-mass spectrometry (SIMS) and transmission electron microscopy (TEM).

**11:30 AM W4.9**
FABRICATION AND CHARACTERIZATION OF GaN JUNCTION FIELD EFFECT TRANSISTORS. L. Zhang, A.G. Baca, R.J. Shul, P.C. Chang, C.G. Willison, Sandia National Laboratories, Albuquerque, NM; L.F. Lester, University of New Mexico, Center for High Technology Materials, Albuquerque, NM; U.K. Mishra, S.P. Denbarrs, Department of Electrical and Computer Engineering, University of California, Santa Barbara, CA; J.C. Zolper, Office of Naval Research, Arlington, VA.

Junction field effect transistors (JFET) were fabricated on a GaN epitaxial structure grown by metal organic chemical vapor deposition. The DC and microwave characteristics, as well as the high temperature performance of the devices were studied. These devices exhibited excellent pinch-off and a breakdown voltage that agreed with theoretical predictions. An extrinsic transconductance of 48 mS/mm was obtained with a maximum $I_{DS}$ of 270 mA/mm. The microwave measurement showed an $f_T$ of 6 GHz and an $f_{max}$ of 12 GHz. Both the drain current and the extrinsic transconductance were found to decrease with increasing temperature, possibly due to lower electron mobility at elevated temperatures. These JFETs exhibit a significant current reduction after a high drain bias is applied, which is attributed to a partially depleted channel caused by trapped hot-electrons in the semi-insulating GaN buffer layer.

**11:45 AM W4.10**
TWO-DIMENSIONAL ELECTRON GAS PROPERTIES IN AlInGaN HETEROSTRUCTURES. S.F. LeBoeuf; M.E. Aumer; F.G. McIntosh; S.M. Bedair; Department of Electrical and Computer Engineering, North Carolina State University, Raleigh, NC.

The successful growth of AlInGaN quaternary alloys has provided near lattice-matched III-nitride heterostructures yielding device-quality, 2DEGs (two dimensional electron gases) at the hetero-interfaces. AlInGaN/InGaN/GaN superlattices, as well as AlInGaN/InGaN, AlGaN/InGaN, and GaN/InGaN single heterostructures, were grown via atmospheric pressure MOCVD in a vertical reactor. The resulting AlInGaN films were nearly lattice-matched to the underlying InGaN layers with a band gap nearly equal to that of GaN. Capacitance-voltage tests were performed on the samples in order to characterize and compare the carrier profiles of the heterostructures. The magnitude and shape of the resulting AlGaN/InGaN and GaN/InGaN carrier profiles suggest that strain-related piezoelectric fields are affecting the 2DEG in both heterostructures. In contrast, carrier profiles of the lattice-matched AlInGaN/InGaN heterostructures do not exhibit a piezoelectric dependency. We will report on the possible origins of this observation. Lattice-matched heterostructures can be of particular use in the design of strain-free TEGFETs (two-dimensional electron gas FETs) due to the potential for high-density 2DEGs without carrier scattering by strain-induced defects at the hetero-interface. As a further benefit, lattice-matched AlInGaN/InGaN heterostructures would facilitate the fabrication of nitride-based enhancement-mode TEGFETs by nullifying the vexatious limitation on critical layer thickness currently associated with AlGaN/InGaN heterostructures.

SESSION W5: ELECTRONIC AND STRUCTURAL CHARACTERIZATION
Chair: Michael S. Shur
Tuesday Afternoon, November 30, 1999
Room 302 (H)

**1:30 PM *W5.1**
POLARIZATION EFFECTS AND NANOSCALE ELECTRONIC PROPERTIES IN NITRIDE SEMICONDUCTOR HETEROSTRUCTURES. E.T. Yu, K.V. Smith, X. Dang, P.M. Asbeck and S.S. Lau, University of California, San Diego, La Jolla, CA.

The importance of spontaneous and piezoelectric polarization effects in nitride semiconductor heterostructures has, by now, been well established. We will discuss these effects and their role in the analysis, design, and engineering of nitride heterostructure field-effect transistor structures. In addition, recent studies have shown that polarization effects combined with the presence of a variety of defect structures, e.g., dislocations, and of local inhomogeneities in composition and layer thickness, can lead to pronounced local variations in electronic properties. We will discuss studies in which proximal probe techniques, most notably scanning capacitance microscopy, have been used to characterize local electronic properties in nitride heterostructures. Acquisition and analysis of scanning capacitance images as a function of bias voltage allows electronic structure to be probed with nanoscale spatial resolution both laterally and in depth. Pronounced lateral variations in threshold voltage are observed at length scales of -0.1$\mu$m to >2$\mu$m in AlGaN/GaN heterostructure field-effect transistor structures. Analysis of image contrast as a function of bias voltage indicates that these variations arise primarily from local variations in AlGaN layer thickness. In addition, a variety of localized features in electronic structure are observed that appear to arise from fixed charge distributions associated with threading dislocations.

**2:00 PM *W5.2**
MICROSTRUCTURE, STRAIN, AND PHASE SEPARATION IN NITRIDE DEVICE MATERIALS. Linda T. Romano, Xerox Palo Alto Research Center, Palo Alto, CA

InGaAlN materials are a different class of semiconducting materials compared to other III-V compounds, having both a greater hardness and a higher melting point, and therefore more similar to ceramics. Furthermore the crystal structure of the nitrides used for commercial LEDs and laser diodes is hexagonal compared to the cubic structure found for other III-Vs, resulting in very different mechanisms for defect formation. In cubic III-Vs, dislocations created during growth can glide and intersect other dislocations due to the easy glide system favored along the growth direction. However in the nitrides, the threading dislocations that are created during growth are formed along the $\{10\bar{1}0\}$ prism planes and not the easy glide {0001} basal plane. Although many of the threading dislocations can be eliminated by epitaxial layer overgrowth, the high hardness of these materials results in device structures that can sustain large strains and remain pseudomorphic well beyond the critical thickness found for cubic materials. Dislocations are not found to relieve strain by either bending or nucleating at the lattice mismatched layers found within the device. Relaxation of tensile strain seems to proceed by cracking rather than dislocation formation. The large strains may also inhibit bulk phase separation in these alloys. In this talk, we will discuss $In_xGa_{1-x}$ N/GaN multiple quantum well (MQW) LED structures with indium compositions up to x = 0.33 (determined by Rutherford backscattering).[1] The as grown structures were analyzed by transmission electron microscopy (TEM) and show no indication of phase separation. X-ray diffraction indicated that these QW structures are pseudomophic, and TEM revealed no misfit dislocations along the highly strained well/barrier interface in samples with x < 0.33; only at x = 0.33, misfit dislocations were observed in isolated regions along the interface. The QW structures were subjected to various annealing treatments to induce phase separation. Phase separation only occurred when voids were simultaneously created. However we found that annealing at high nitrogen overpressures (15kbar), suppressed both voids and phase separation. After annealing, defects were found near inversion domains (IDs) in the GaN:Mg overlayer above the QWs. The topic of cracking and residual stress will be addressed by showing results of a study involving GaN layers doped with various amounts of Si.[2] It was found that cracking occurs in the GaN films above a critical doping level of Si and film thickness. A combination of XRD and TEM results show that the in-plane lattice constant increases with the doping concentration and is associated with the onset of microcracking. Micro-raman measurements indicate that the stress relief associated with the cracking is very local to where the crack is formed.
[1] L.T. Romano, M.D. McCluskey, C.G. Van De Walle, M. Kneissl, D.P. Bour, T. Suski, J. Jun, submitted Appl. Phys. Lett.
[2] L.T. Romano, C.G. Van De Walle, J.A. Ager III , W. Gotz , R.S. Kern , submitted Appl. Phys. Lett

**2:30 PM W5.3**
ELECTRON HOLOGRAPHIC OBSERVATIONS OF GROUP III NITRIDE INTERFACES AND QUANTUM WELLS.
M.R. McCartney, Center for Solid State Science, Arizona State University, Tempe, AZ; D. Cherns, H.H. Wills Physics Laboratory, University of Bristol, Bristol, UNITED KINGDOM; D. Bour, Xerox Palo Alto Research Center, Palo Alto, CA; F.A. Ponce, Department of Physics, Arizona State University, Tempe, AZ.

In electron holography, interference between the reference wave and the wave traversing the sample is used to extract information about the local internal potential. We have used this technique to study internal fields at interfaces of various nitride semiconductor heterojunctions. In this paper, we present results of studies involving InGaN/GaN and InGaN/AlGaN heterojunctions with lattice mismatch in the range of 2 to 6%. It has been observed that InGaN grows pseudomorphically without plastic relaxation of the lattice mismatch and that heterojunctions involving InGaN tend to be highly coherent. From the phase shift determinations at these junctions and from the relative phase variation across the film, we have extracted the piezoelectric component of the internal field. Fields on the order of one MeV/cm are clearly observed. It is also found that dislocations relax the piezoelectric field in most cases. These results indicate that dislocations play a role in widening the light emission width in InGaN quantum wells.

**2:45 PM W5.4**
ATOMIC STRUCTURE OF EXTENDED DEFECTS IN GaN.
Pierre Ruterana, Valerie Potin and Gerard Nouet, Laboratoire d'Etudes et de Recherches sur les Materiaux, UPRESA CNRS 6004, IMSRA, Caen, FRANCE.

The active layers of wurtzite GaN layers contain large densities of extended crystallographic defects (10 10 $cm^{-2}$), which are threading dislocations, nanopipes, {11-20} stacking faults, and {10-10}inversion domains. It is now clearly established that the large majority of the threading dislocations are pure edge with their line parallel to the c growth axis. For such defects, the atomic structure of the cores are studied by HREM along [0001]. In the investigated samples, three configurations have been found for these pure edge dislocations, mainly inside high angle grain boundaries where the 4 atom ring cores can be stabilized. Two atomic configurations for the {11-20} stacking fault have been observed in (Ga-Al) N layers; they are related by a $1/6< 10-10 >$ stair rod dislocation. Such defects form on steps in epitaxial layers on the top of (0001) 6H-SiC; on (0001) sapphire, they appear on coalescence of two adjacent islands related by the I1 stacking fault. In our investigations of the {10-10} inversion domains, it was shown that they only form in GaN layers grown on (0001) sapphire. A configuration corresponding to the Holt model was observed for these domains boundaries, as well as another in which no N-N or Ga-Ga bonds occur inside the boundary, the two

configurations are related by a c/2 translation. These boundaries are quite efficient in reducing the shift along c which is introduced by substrate surface steps.

**3:30 PM W5.5**
TEM STUDY OF BULK AlN GROWTH BY PHYSICAL VAPOR TRANSPORT. W.L. Sarney, L. Salamanca-Riba, R.D. Vispute, Dept. of Materials & Nuclear Engineering, University of Maryland, College Park, MD; T. Hossain, P. Zhou, H.N. Jayatirtha, M. Spencer, Materials Science Research Center of Excellence, Howard University, Washington, DC; V. Dmitriev, TDI Inc., Gaithersburg, MD; Y. Melnik, A, Nikolaev, A.F. Ioffe Institute, St. Petersburg, RUSSIA; K.A. Jones, U.S. Army Research Laboratory, Adelphi, MD.

Despite the rapid progress made in nitride based semiconductor film growth, there is still no suitable isomorphic substrate. AlN and GaN are typically grown on SiC, which is extremely expensive, or on Sapphire, which is cheaper but has a large lattice mismatch with the nitride based films. Pure GaN substrates are difficult to produce because of the extremely high vapor pressure of nitrogen over GaN. Bulk AlN is easier to produce since it has a much lower vapor pressure of nitrogen. In this study, bulk AlN was grown by physical vapor transport by the decomposition of AlN powder in the presence of ambient nitrogen. The growth temperature range was 2000-2300 C with nitrogen pressures of 100 - 600 Torr. The separation between the seed and AlN powder was in the range of 4 mm under a temperature gradient of 1 - 3 C/mm. The growth rate was varied between 10 and 50 microns per hour. We investigated two different seed crystals, including singular 6H SiC and 3.5 degrees off-axis 6H SiC. Transmission electron microscopy was used to examine the crystallinity and defect morphology of the AlN. Auger electron microscopy, atomic force microscopy, x-ray diffraction, and scanning electron microscopy were also used to characterize the AlN. The full width half maximum determined from rocking curve experiments is not drastically different from that obtained from thin AlN films grown on SiC. AFM and SEM show a three dimensional spiral growth morphology for the AlN grown on on-axis SiC, and a step morphology for the AlN grown on off-axis SiC. Preliminary TEM analysis shows that the AlN is well oriented with the SiC. We will discuss the quality of the bulk AlN we have grown and compare it to the quality of AlN films grown as potential buffer layers in previous experiments.

**3:45 PM W5.6**
DISLOCATION PROCESSES IN AlN AND GaN BULK CRYSTALS GROWN BY HVPE. M. Albrecht, H.P. Strunk, Universitaet Erlangen-Nuernberg, Institut fuer Werkstoffwissenschaften, Lehrstuhl Mikrocharakterisierung, Erlangen, GERMANY; I.P. Nikitina, A.E. Nikolaev, Yu.V. Melnik, K. Vassilevski, A.F.Ioffe Physico-Technical Institute, St. Petersburg, RUSSIA. V.A. Dmitriev, Ioffe Physico-Technical Institute, St. Petersburg, RUSSIA; TDI, Inc., Gaithersburgh, MD and Materials Research Center of Excellence, School of Engineering, Howard University, NW Washington, DC.

GaN layers grown on foreign substrates contain misfit dislocations induced by the lattice mismatch between substrate and layer. These misfit dislocations, when extending into the layer, form threading dislocations, that may affect electronical and optical properties. Moreover, high residual strains or even cracking may occur upon cooling to room temperature due to a difference in thermal expansion coefficient between substrate and overlayer. Tackling these problems means firstly understanding the fundamental dislocation processes. While dislocation processes in heteroepitaxial cubic systems are well examined, up to now very few analogous work exists for nitrides. We in this work analyse by means of transmission electron microscopy and x-ray diffraction some of the basic processes that take place in GaN and AlN crystals grown by hydride vapour phase epitaxy (HVPE) to thicknesses of 100 to 200 $\mu$m. We show that the defect populations of these crystals are controlled by the initial growth process which determines the Burgers vector selection. The dislocation populations are linked to important aspects of bulk crystal properties. When only a-type dislocations are present an efficient reduction mechanism reduces the dislocation density to $4x10^5$ $cm^{-2}$ or less, but the crystal tend to crack on cooling from growth temperature. When the dislocation are distributed on all possible Burgers vectors in equal density only a small density reduction occurs (two orders in magnitude at 100$\mu$m). However these crystal show a high resistance against cracking. The cracking behaviour is a consequence of the multiplication possibilities for dislocations capable of accommodating thermal strains during cooling. These possibilities depend on the dislocation population. We discuss the impact of these mechanisms on residual strain in thin epitaxial layers, on the design of buffer layers and on dislocation mechanisms in epitaxial laterally overgrown layers.

**4:00 PM W5.7**
THERMAL EXPANSION OF GaN AT LOW TEMPERATURES - A COMPARISON OF BULK AND HOMO- AND HETEROEPITAXIAL LAYERS. V. Kirchner, H. Heinke, S. Einfeldt, D. Hommel, University of Bremen, Institute of Solid State Physics, Bremen, GERMANY; J.Z. Domagala, Institute of Physics, Polish Academy of Sciences, Dept. of X-ray Studies and Electron Microscopy, Warsaw, POLAND; M. Leszczynski, High Pressure Research Center, Unipress, Warsaw, POLAND.

Although thermally induced strain reaches significant values in most epitaxial GaN layers, some of its basic aspects are still uncertain. This concerns the thermal expansion coefficients of GaN, especially at low temperatures, as well as the crucial parameters responsible for different strain states of GaN epilayers. In this paper, the thermal expansion of different GaN samples is studied by high-resolution X-ray diffraction within the temperature range of 10 to 600 K. GaN bulk crystals, a homoepitaxial layer and different heteroepitaxial layers grown both by metalorganic chemical vapour deposition (MOCVD) and molecular beam epitaxy (MBE) were investigated. For the GaN bulk crystals, the temperature dependent thermal expansion coefficients (TEC) were determined and compared to theoretical values. Below 100 K the TEC were found to be nearly zero which has to be taken into account when estimating the thermal strain of GaN layers in optical experiments commonly performed at low temperatures. The homoepitaxial layer and the underlying GaN substrate with a lattice mismatch of $-6 \times 10^{-4}$ showed identical thermal expansion. Comparing the $c$ lattice constants of the homoepitaxial layer and the MBE and MOCVD grown heteroepitaxial layers, the dependence of thermal strain on growth temperature is confirmed. However, the various MOCVD samples generously provided by S. DenBaars (UCSB) and S. Nakamura (Nichia Chem. Ind.) seem to differ significantly as well. Possible reasons for these differences will be discussed.

**4:15 PM W5.8**
THE ROLE OF MULTI BUFFER LAYER TECHNIQUE ON THE STRUCTURAL QUALITY OF GaN. M. Benamara, Z. Liliental-Weber, J.H. Mazur, W. Swider and J. Washburn, E.O. Lawrence Berkeley National Laboratory, Berkeley CA; H. Amano, Meijo University, Dept. of Electrical and Electronic Engineering, Nagoya, JAPAN.

Successive growth of thick GaN layers separated by either LT-GaN or LT-AlN layer have been investigated by transmission electron microscopy techniques. One of the objectives of this growth method was to improve the quality of GaN layers by reducing the dislocation density at the intermediate buffer layers that act as barriers to dislocation propagation. While the use of LT-AlN results in the multiplication of dislocations in the subsequent GaN layers, the LT-GaN reduces dislocations density. Based upon Burgers vector analysis, the efficiency of the buffer layers for the propagation of the different type of dislocations is presented and discussed. LT-AlN buffer layers favors the generation of screw dislocations, leading to a highly defective GaN layer. On the other hand, the use of LT-GaN as intermediate buffer layers appears as a promising method to obtain high quality GaN layer.

**4:30 PM W5.9**
PHYSICAL PROPERTIES OF SILICON DOPED HETERO-EPITAXIAL MOCVD GROWN GaN: INFLUENCE OF DOPING LEVEL AND STRESS. P.R. Hageman, V. Kirilyuk, A.R.A. Zauner, and P.K. Larsen, Research Institute for Materials (RIM), University of Nijmegen, Nijmegen, THE NETHERLANDS.

Especially for the use in laser diodes and high-temperature, high-power electronics, the physical properties of the $n$-type GaN layers is of utmost importance. In the MOCVD growth of GaN, the doping process with silicon as dopant is relatively simple and straight forward. However, it is well known that the relatively low concentration of incorporated silicon has a tremendous influence on the optical and mechanical properties of the material.
Silicon doped layers were grown with MOCVD on sapphire substrates using silane as silicon precursor. The influence of the doping concentration, layer thickness and buffer thickness will be presented in detail in this paper. The buffer layer thickness determines the polarity, and thus the resulting morphology, of the doped GaN layers. The electrical behaviour is characterised using (temperature dependent) Hall measurements. The influence of the layer thickness and polarity (N-side or Ga-side up) on the electrical quality of the material is evaluated. The intensity of the photoluminesence (PL) signal and the peak position of the Donor Bound Exciton (DBE) is depending on the silicon concentration ($10^{17}\,cm^{-3}$ – $10^{19}\,cm^{-3}$). Curiously, the intensity of the UV part of the PL spectra increases as the silicon concentration increases. Due to conduction band renormalisation the DBE position shift towards lower energy position and at very high concentrations even the Mott transition can be observed. These effects will be correlated to the doping level and the amount of stress in the material, which is determined by the layer thickness. Optical differential interference contrast microscopy and scanning electron microscopy (SEM) were used to investigate the morphology of the

layers. To determine the crystal quality and the stress in the layers High Resolution XRD measurements were performed.

**4:45 PM W5.10**
PROBING NITRIDE THIN FILMS IN 3-DIMENSIONS USING A VARIABLE ENERGY ELECTRON BEAM. C. Trager-Cowan, P.G. Middleton, A. Mohammed, S.K. Manson-Smith, I. Osborne, M. Barisonzi and K.P. O'Donnell., Strathclyde Univ, Dept. Physics and Applied Physics, Glasgow, SCOTLAND; W. Van der Stricht, K. Jacobs, I. Moerman and P. Demeester, IMEC-INTEC, University of Gent, Gent, BELGIUM; M.F. Wu and A. Vantomme, KU Leuven, Leuven, BELGIUM.

Thin films incorporating GaN, InGaN and AlGaN are presently arousing considerable excitement because of their suitability for UV and visible light emitting diodes and laser diodes. However, because of the lattice mismatch between presently used substrates and epitaxial nitride thin films, the films are of variable quality. We are presently using a number of novel techniques in the scanning electron microscope, namely cathodoluminescence (CL) imaging, CL spectroscopy and electron backscattered diffraction (EBSD), to investigate both the structural and optical properties of such films in 3-dimensions. Information in the 3rd dimension is extracted by acquiring data at different electron beam energies. We are using these techniques to 1) map and depth profile strain in the films, where the strain is due to the lattice mismatch mentioned earlier; 2) map and depth profile defect distributions; 3) investigate zinc blende inclusions in thin films of predominantly wurtzite material, and 4) map and depth profile the variation in alloy composition in alloy films. Results to date include (i) the acquisition of CL images of an InGaN/GaN multiple quantum well (MQW) grown on an epitaxially lateral overgrown GaN (ELOG) layer. We have shown that the luminescence efficiency of both the GaN and the MQW is improved for material lying above the stripes of the $SiO_2$ mask compared to that above the windows of the mask or unpatterned material; (ii) the depth profiling of the indium mole fraction of a 0.4 mm InGaN epilayer using CL spectroscopy. The CL peak was found to shift from $\approx$ 2.80 to $\approx$ 2.85 eV, which shows that the In content decreases with increasing depth; (iii) the acquisition of EBSD patterns from GaN epilayers. EBSD allows the comparison of the crystalline quality of epilayers grown under different growth conditions.

SESSION W6: GROWTH – MOCVD, HVPE, BULK
Chair: Hiroshi Amano
Wednesday Morning, December 1, 1999
Room 302 (H)

**8:30 AM *W6.1**
COMPARISON OF InGaN LAYERS GROWN ON BULK GaN AND SAPPHIRE SUBSTRATES. Shiro Sakai, Tokushima University, Dept of Electrical and Electronic Engineering, Minami-josanjima, Tokushima, JAPAN.

InGaN/GaN SQW(Single Quantum Well) and MQW (Multiple Quantum Well) were grown on sapphire and bulk GaN substrates and compared. A bulk GaN substrate was either a free-standing bulk GaN crystal prepared by the sublimation method or a thick GaN film prepared by the direct synthesis of Ga metal and ammonia on MOCVD-grown GaN/sapphire substrate. Both crystals had high crystal perfection with low dislocation density. SQW and MQW grown on these substrates were characterized by TEM , CL and PL. A clear phase separation in sub-micron-range-domains with different indium composition was observed in thick-InGaN films grown at relatively low temperature on sapphire substrates but not on bulk GaN. Although such a phase separation was not seen in thin-InGaN grown at higher temperature, abnormal temperature behavior of PL peak wavelength, which was attributed to the existence of the band tail was observed in all InGaN layers grown on sapphire. The band tail became large with increasing indium composition. These results indicate that a dislocation plays a key role in the phase separation and compositional fluctuation in InGaN films. The behavior of dislocation-free-InGaN grown on GaN substrate is quite normal.

**9:00 AM *W6.2**
OMVPE Growth of (Al,Ga,In)N for UV Optoelectronics. Jung Han and M.H. Crawford, Sandia National Laboratories, Albuquerque, NM.

Nitride-based ultraviolet (UV) light source is attractive for applications such as energy-efficient indoor lighting and various forms of chemical sensing. The development of UV emitters, however, faces challenges in both device design and material growth. Issues unique to the growth of nitride-based UV emitters, specifically the control of structural coherency and the enhancement of optical efficiency, are discussed in this work. It is shown that the common configuration of nitride-based visible-light emitters, based on the growth of ternary (AlGaN and GaInN) heterostructures on thick binary GaN buffers, imposes stringent constraints to the implementation of UV emitters; the demand of a higher barrier with AlGaN implies an increased tensile mismatch to GaN. Two approaches to circumvent this issue will be discussed in this paper: i) the use of a thick AlGaN ternary buffer and ii) the employment of quaternary AlGaInN as wider bandgap nitrides lattice-matched to GaN. The viability of the employment of binary GaN as an active layer for UV emitters was also studied. Improvement of optical efficiency was achieved by optimizing the growth condition of GaN and the introduction of indium. Sandia is a multiprogram laboratory, operated by Sandia Corporation, a Lockheed Martin company, for the United States Department of Energy, under contract DE-AC04-94AL85000.

**9:30 AM W6.3**
HOMOEPITAXIAL GROWTH ON MISORIENTED GaN SUBSTRATES BY MOCVD. A.R.A. Zauner, J.L. Weyher, V. Kirilyuk, P.R. Hageman, and P.K. Larsen, Dept. Experimental Solid State Physics III, Research Institute for Materials, University of Nijmegen, THE NETHERLANDS; S. Porowski, High Pressure Research Center, Polish Academy of Science, Warsaw, POLAND.

The surface morphology of GaN layers depends significantly on the polarity of the layers. GaN growth in the [0001] direction, or on the so-called Ga-side, can lead to smooth and transparent films. For growth predominantly in the [000$\bar{1}$] direction (N-side), the layer is tending to form hexagonal pyramids. The main advantage for growth on the N-side of GaN bulk crystals is the fact that this side can be mechano-chemically polished to obtain epi-ready substrates for homo-epitaxial growth, this is in contrast with the Ga-side that can only be mechanically polished. For device applications, formation of hexagons on top of the surface should be avoided. A common way to avoid growth features on top of the surface is the use of misoriented substrates. In the present work the surface morphology of homo-epitaxial GaN layers grown by low-pressure MOCVD was studied for different off-angle orientations, 2° and 4°, from the [000$\bar{1}$] direction of GaN substrates. It was found that the formation of hexagonal pyramids on these N-side substrates could be suppressed by using a large enough misorientation. Optical differential interference contrast microscopy, scanning electron microscopy (SEM), and atomic force microscopy (AFM) were used to investigate the morphology of the layers. The optical quality, provided by photoluminescence (PL) measurements, is in the order of 1 meV as expected for homo-epitaxial growth.

**9:45 AM W6.4**
CRITICAL LAYER THICKNESS OF GaN/$In_xGa_{(1-x)}N$ SYSTEM. C.A. Parker, M.J. Reed[1], J.C. Roberts, S.X. Liu[1], N.A. El-Masry[1], and S.M. Bedair Dept of Electrical and Computer Engineering, NC State Univ, Raleigh, NC; [1]Dept of Materials Science and Engineering, NC State Univ, Raleigh, NC.

Much effort has been directed towards the use of $In_xGa_{(1-x)}N$/GaN heterostructures for device applications where the strained $In_xGa_{(1-x)}N$ layers were kept well below the so called critical layer thickness (CLT). No definite information is available about the value of the critical layer thickness of $In_xGa_{(1-x)}N$ heterostructures or double heterostructures (DH) on thick GaN. We present an approach to determine the critical layer thickness of $In_xGa_{(1-x)}$/GaN heterostructures grown by atmospheric MOCVD. The $In_xGa_{(1-x)}$ films investigated have values of x between 0 and 0.20 as determined by x-ray diffraction and thickness of up to 1 $\mu$m determined by cross-sectional TEM, SEM, and depth profiling capacitance-voltage measurements (CV). Photoluminescence (PL) is employed to determine the optical emission characteristics of the films. CLT was determined by monitoring the evolution of PL emission, carrier concentration, and film resistivity as the $In_xGa_{(1-x)}$ film thickness is increased. As the $In_xGa_{(1-x)}$ film thickness increases, the onset of relaxation occurs. A red shift in band edge emission, the appearance of deep level emission, a transition to three-dimensional growth, an increase in film resistivity, and a decrease in free carriers accompany this relaxation. The CLT is deduced from the PL data by two different approaches: 1.) The CLT is considered to be the thickness at which the bandgap of strained films equals that of relaxed films, or 2.) The onset of deep level emission, assumed to arise from structural defects at the $In_xGa_{(1-x)}$/GaN interface, occurs when the film thickness exceeds the CLT. Both approaches give equivalent critical thickness values for the InGaN films and are confirmed by electrical measurements of the samples. The critical layer thickness estimates determined in this fashion are consistent with off-axis x-ray diffraction data and SEM observations of surface morphology. It should be noted that our estimates of CLT in the $In_xGa_{(1-x)}$/GaN system are larger than those previously reported for other semiconductors. We will discuss the nature of the relaxation process in $In_xGa_{(1-x)}$ heterostructures and DHs and report the CLT of the $In_xGa_{(1-x)}$ as a part of these structures. Additionally, we will discuss the effect of InGaN thickness on the electrical properties of the InGaN/GaN structure.

**10:30 AM W6.5**
AlN WAFERS FABRICATED BY HYDRIDE VAPOR PHASE EPITAXY. A. Nikolaev, I. Nikitina, A. Zubrilov, M. Mynbaeva, Ioffe Institute and Crystal Growth Research Center, St. Petersburg, RUSSIA; Yu. Melnik and V. Dmitriev, TDI, Inc., Gaithersburg, MD.

AlN is attractive substrate material for a fabrication of a large number of devices based on group III nitrides including UV photodetectors, short wavelength emitters, and microwave power transistors. Due to technological difficulties, large area AlN crystals (>1 square cm) have not been reported yet [1]. In this paper, we report on 3x3 cmxcm AlN wafers fabricated by hydride vapor phase epitaxy (HVPE). This method is well known as an effective tool for the fabrication of GaN free-standing wafers [2,3,4]. Recently, we reported on high quality thin AlN layers grown on SiC substrates by HVPE [5]. Now we successfully applied HVPE technology to grow AlN bulk crystals. AlN thick layers were grown on SiC, sapphire and Si substrates by HVPE. Growth rate was up to 60 microns per hour. After the growth of AlN layers, initial substrates were removed resulting in free-standing AlN wafers. Si substrates were removed by wet chemical etching. SiC and sapphire substrates were removed by reactive ion etching. The maximum thickness of AlN layer was 0.8 mm. AlN free-standing single crystal wafers with a thickness ranging from 0.1 to 0.8 mm were studied by x-ray diffraction, atomic force microscopy, optical absorption, and cathodoluminescens. The detailed investigation of crystal structure and defect density will be presented and discussed. The growth method will be discussed in terms of scaling for large AlN wafers. [1] G.A. Slack, Mat. Res. Soc. Symp. Proc. 512 (1998) 35; [2] T. Detchprohm et al., Appl. Phys. Letters 61 (1992) 2688, [3] Yu. Melnik et al., Symp. Proc. Vol. 482 (1998) 269, [4] M.K. Kelly et al., Jpn. J. Appl. Phys. Vol. 38, Pt.2, No. 3A (1999) L217, [5] Yu.V. Melnik et al., MRS Symp. Proc. Vol. 482 (1998) 245.

**10:45 AM W6.6**
GAN 20 MM DIAMETER ingots GROWN FROM MELT-SOLUTION BY SEEDED TECHNIQUE. V. Sukhoveev, Crystal Growth Research Center, St. Petersburg, RUSSIA; V. Ivantsov, I. Nikitina, A. Babanin, Ioffe Institute, St. Petersburg, RUSSIA; V. Dmitriev, TDI, Inc., Gaithersburg, MD.

Lack of GaN substrate materials limits performance of GaN-based devices including light emitters and microwave power transistors. Currently, GaN-based devices are being made by heteroepitaxy on sapphire or silicon carbide substrates resulting in a high defect density and stress in the device structures. A technology for the fabrication of true bulk GaN crystals is absent. Maximum volume of GaN crystals reported so far did not exceed 0.6 cubic cm [1,2]. In this paper, we describe GaN ingots with a volume of about 4.5 cubic cm grown from melt-solution [3]. This is the first successful attempt to grow GaN by seeded technique from the liquid phase. GaN ingots up to 2 cm in diameter and 1.5 cm in length were grown from Ga-based melt in the temperature range from 900 to 1000 C at a pressure less than 2 atm. Normal growth rate was about 2 mm per hour. Grown ingots were sliced and resulted GaN wafers were studied by x-ray diffraction, Auger electron spectroscopy, and Hall technique. Results of material investigation will be presented. These GaN wafers were used as substrates for GaN homoepitaxy. Epitaxial layers were grown by hydride vapor phase epitaxy. Properties of the homoepitaxial layers will be discussed. [1] I. Grzegory et al., Mat. Res. Soc. Symp. Proc. 482 (1998) 15; [2] M.K. Kelly et al., Jap. J. Appl. Phys. 38, Pt. 2, N3A (1999) L218; [3] V.A. Ivantsov et al., Mat. Res. Soc. Symp. 468 (1997) 143.

**11:00 AM W6.7**
PREPARATION AND CHARACTERIZATION OF SINGLE CRYSTAL ALUMINUM NITRIDE SUBSTRATES. J. Carlos Rojo, Crystal IS, Inc., Latham, NY; Leo J. Schowalter, Yuriy Shusterman, Rongjun Wang, Ishwara Bhat, Katharine Dovidenko and Glen A. Slack, Rensselaer Polytechnic Institute, Troy, NY.

While III-nitride epitaxy offers great potential for optoelectronic, high temperature and high power devices, the common use of sapphire substrates has many disadvantages. The use of single crystal III-nitride substrates should allow improved epitaxial growth, enhanced thermal and chemical compatibility, as well as increased thermal conductivity. At Crystal IS, we have succeeded in producing 1-cm-diameter boules of AlN and plan to produce larger diameter crystals in the near future. We have also prepared a-face and c-face single crystal AlN substrates using a chemical mechanical polishing (CMP) process that successfully removes mechanical damage while resulting in an atomically smooth surface. High quality epitaxial AlN and $Al_xGa_{1-x}N$ layers have been grown by organo-metallic vapor-phase epitaxy (OMVPE) on the AlN substrates and have been characterized with Rutherford backscattering/ion channeling spectroscopy (RBS), AFM, TEM, optical microscopy, double-crystal x-ray diffraction (XRD), and electrical measurements. Ion channeling along the [11-20] axis gave a minimum yield of 1.5% for a homoepitaxial AlN layer and 2.2% for heteroepitaxial $Al_{0.5}Ga_{0.5}N$, indicating excellent crystal quality. A resistivity of 20 Ohms-cm and a mobility of 20 $cm^2$/V-s was measured in a Si-doped, 1-micron-thick, $Al_{0.5}Ga_{0.5}N$ grown epitaxially on the AlN substrates.

**11:15 AM W6.8**
GROWTH OF CRACK-FREE THICK AlGaN LAYER AND ITS APPLICATION TO GaN BASED LASER DIODES. Isamu Akasaki, Dept. of Electrical and Electronic Engineering and High-Tech Research Center, Meijo University, Nagoya, JAPAN; Satoshi Kamiyama, High-Tech Research Center, Meijo University, Nagoya, JAPAN; Theeradetch Detchprohm, High-Tech Research Center, Meijo University, Nagoya, JAPAN; Tetsuya Takeuchi, Dept. of Electrical and Electronic Engineering, Meijo University, Nagoya, JAPAN; Hiroshi Amano, Dept. of Electrical and Electronic Engineering and High-Tech Research Center, Meijo University, Nagoya, JAPAN.

In the field of group-III nitrides, hetero-epitaxial growth has been one of the most important key technologies. A thick AlGaN alloy with higher AlN molar fraction is difficult to grow on sapphire substrate, because the alloy layer is easily cracked. It is thought that one cause of generating cracks is a large lattice mismatch between an AlGaN and a GaN, which is generally grown just on a low temperature buffer layer and under the AlGaN layer. We have achieved crack-free $Al_{0.06}Ga_{0.94}N$ layer with the thickness of more than $1\mu$ using underlying $Al_{0.03}Ga_{0.97}N$ layer. The underlying $Al_{0.03}Ga_{0.97}N$ layer is directly grown on the low temperature-grown buffer layer. Since a lattice mismatch between the underlying $Al_{0.03}Ga_{0.97}N$ layer and top $Al_{0.06}Ga_{0.94}N$ layer is relatively small, the generation of cracks is thought to be suppressed. This technology is applied to a GaN-based laser diode structure, in which thick n- $Al_{0.06}Ga_{0.94}N$ cladding layer grown on the underlying $Al_{0.03}Ga_{0.97}N$ layer improves optical confinement and single-robe far field pattern in vertical direction. The threshold current is as low as 230mA in a $3\mu$ ridge stripe laser structure, which is comparable to or better than that of conventional GaN-based nitride laser diodes. This result indicates that the quality of epitaxial layers is sufficient enough for the performance of laser diodes.

**11:30 AM W6.9**
STRAIN ENGINEERING IN AlInGaN/InGaN QUANTUM WELLS. Michael E. Aumer, S.F. LeBoeuf, F.G. McIntosh, S.M. Bedair, North Carolina State University, Dept of Electrical and Computer Engineering, Raleigh, NC.

The large lattice mismatch between AlN, GaN, InN and their respective ternary alloys results in highly strained heterostructures. The optical and electrical properties of GaN/InGaN and AlGaN/InGaN quantum wells (QWs) are greatly effected by the in-plane compressive stress and resulting piezoelectric field. A better understanding of strain effects on InGaN QWs would be possible if the InGaN layer could also be lattice matched or subjected to tensile stress. We present a new approach to the investigation of strain effects in InGaN-based QWs using the quaternary alloy AlInGaN. A test structure was designed to vary the stress experienced by an $In_{0.1}Ga_{0.9}N$ quantum well. The structure is a nearly lattice matched AlInGaN/$In_{0.1}Ga_{0.9}N$/AlInGaN QW with an AlInGaN band gap equal to that of GaN. The QW is grown on a thick layer of fully relaxed $In_xGa_{1-x}N$. The QW is lattice matched to the underlying $In_xGa_{1-x}N$ for x = 0.1. Employing sufficiently thin AlInGaN as the confinement barrier permits pseudomorphic growth of the quantum well structure; therefore, if x> 0.1, the well is subjected to tensile stress. Compressive stress is created in the well for x< 0.1. Compared to the peak position of the lattice matched AlInGaN/$In_{0.1}Ga_{0.9}N$/AlInGaN quantum well, we observed a red-shift in the luminescence for the tensilely stressed case and a blue-shift in the luminescence for compressive stress. Also, we observed strain-related changes in the carrier concentration profile and the two-dimensional electron gas using capacitance-voltage measurements. This behavior is explained by the variation of the in-plane stress and subsequent changes in the resulting piezoelectric field. We will report on how the engineering of strain can be used to manipulate the optical and electrical properties of InGaN-based QWs.

**11:45 AM W6.10**
FACETING OF VICINAL GaN(0001) DURING MOCVD GROWTH AND ANNEALING. M.V. Ramana Murty[a], A. Munkholm[b], G.B. Stephenson[a], C. Thompson[a,c], J.A. Eastman[a], O. Auciello[a], R. Jothilingam[d], P. Fini[d], S.P. DenBaars[d], and J.S. Speck[d]; [a)]Materials Science Div., Argonne National Laboratory, Argonne, IL; [b]Chemistry Div., Argonne National Laboratory, Argonne, IL; [c]Dept. of Physics, Northern Illinois University, Dekalb, IL; [d]Materials Dept., University of California, Santa Barbara, CA.

Device quality GaN is normally grown at high temperatures in the step-flow regime. A study of the evolution of step morphology under

these conditions can shed light on the surface kinetics relevant to device fabrication. We have conducted a real-time grazing incidence X-ray scattering study of the evolution of the step structure on vicinal GaN (0001) surfaces during MOCVD growth and annealing. In addition, we measured growth and evaporation rates using *in situ* optical interferometry. On a nominally 2° miscut surface, MOCVD growth at 1000°C leads to faceting (step bunching). Subsequent annealing without growth results in a uniform step density with monolayer height steps. We will compare the behavior of singular and vicinal GaN(0001) surfaces and discuss the kinetics of the surface morphology evolution on vicinal surfaces.
This work was supported by the U.S. DOE, BES–DMS under contract W-31-109-ENG-38, the NSF under grant DMR–9704201, and the State of Illinois under HECA.

SESSION W7: PANEL DISCUSSION
1:30 PM - 3:00 PM
Wednesday Afternoon, December 1, 1999
Room 302 (H)

**1:30 PM PANEL DISCUSSION:**
WIDE BAND GAP SEMICONDUCTOR RESEARCH IN EUROPE
**Panel:**
Vladimir Dmitriev - TDI, Inc.
Steve DenBaars - University of California-Santa Barbara
Paul Chow - Renssealer Polytechnic Institute
Michael Shur - Renssealer Polytechnic Institute
Michael Spencer - Cornell University
George White - Georgia Tech
Usha Varshney - National Science Foundation
John Zavada - Army Research Office
John Zolper - Office of Naval Research

SESSION W8: GROWTH – MBE, CUBIC GaN, GaAsN, Si SUBSTRATES
Chair: Thomas H. Myers
Wednesday Afternoon, December 1, 1999
Room 302 (H)

**3:30 PM *W8.1**
HIGH QUALITY AlGaN/GaN GROWN BY MOLECULAR BEAM EPITAXY. M.J. Jurkovic, L.K. Li, and W.I. Wang, Department of Electrical Engineering, Columbia University, New York, NY.

High quality AlGaN/GaN has been achieved by molecular beam epitaxy (MBE) using ammonia as the nitrogen source at a growth rate of 1um/hr. All samples were grown on c-plane sapphire substrates in a GEN II MBE system equipped with an ammonia gas injector and a SVT Associates (SVTA) RF plasma source. Reflection high energy electron diffraction (RHEED) revealed a sharp surface reconstruction during growth, indicative of atomic smoothness of the films. From the ammonia flow rate dependence of the unintentional electron concentration, N-vacancies were identified as the residual donors. Under optimized growth conditions, high mobility two-dimensional electron gas (2DEG) has been achieved with electron mobilities as high as 6000 $cm^2/Vs$ at 77 K. The results of p-type doping will also be presented.
Work supported by ONR MURI monitored by Dr. C.E.C. Wood.

**4:00 PM *W8.2**
GROWTH AND PROPERTIES OF CUBIC GaN LAYERS AND (Al,Ga,In)N HETEROSTRUCTURES. Klaus H. Ploog, Paul Drude Institute for Solid State Electronics, Berlin, GERMANY.

In this talk we summarize our work on growth and properties of cubic GaN layers and (Al,Ga,In)N heterostructures on GaAs(001) substrates. The work was motivated by the potential advantages that cubic nitrides would offer for applications in optoelectronic devices compared to their hexagonal counterparts, provided they can be produced in sufficiently high quality. These advantages include visible light emission from In(x)Ga(1-x)N at lower x due to the smaller band gap, fabrication of laser facets by simple cleavage, band-gap engineering by strain-induced effects, smaller electron effective mass, and higher saturated drift velocity. However, as cubic nitrides represent the respective metastable phases and as lattice-matched substrates do not exist, we had to develop specific strategies to synthesize cubic GaN layers of high phase purity on GaAs(001) substrates by plasma-assisted MBE. In a two-step process that allow to optimize the nucleation stage and the subsequent layer growth independently, we were able to produce single-phase cubic GaN layers and (Al,Ga,In)N heterostructures, as confirmed by high-resolution XRD, SAD, and TEM. Despite the high density of structural defects, caused by the huge lattice mismatch of 20 % to the underlying substrate, the emission intensity and optical gain of cubic GaN layers at room temperature are comparable to those of hexagonal GaN. However, although sharp In profiles and In contents up to 40 % were achieved in (Al,Ga,In)N heterostructures and quantum wells, the optical properties of those In containing cubic nitrides must be improved further before we can get a conclusive answer to the question: Are cubic nitrides viable materials for optoelectronic devices?

**4:30 PM W8.3**
HIGH QUALITY GaN AND AlN GROWN ON Si(111) BY GAS SOURCE MOLECULAR BEAM EPITAXY WITH AMMONIA. S.A. Nikishin, N.N. Faleev, V.G. Antipov, S. Francoeur, L. Grave de Peralta, G.A. Seryogin, H.Temkin, Dept of Electrical Engineering, Texas Tech Univ., Lubbock, TX; M. Holtz, T.I. Prokofyeva, Dept of Physics, Texas Tech Univ., Lubbock, TX; S.N.G. Chu, Lucent/Bell Labs, Murray Hill, NJ; A.S. Zubrilov, V.A. Elyukhin, Ioffe Physical-Technical Inst., St. Petersburg, RUSSIA; Yu. Melnik, V. Dmitriev, TDI, Inc., Gathersburg, MD.

We describe the growth of high quality GaN and AlN on Si(111) by gas source molecular beam epitaxy (MBE) with ammonia. Epitaxial layers grown on Si, evaluated by high resolution x-ray diffraction, atomic force microscopy, Raman spectroscopy, and 77 and 300 K photoluminescence, are comparable to the best samples grown on sapphire or SiC, by any technique. The initial deposition of Al, carried out at 1130-1190K, resulted in a very rapid transition to two-dimensional growth mode of AlN. Under optimum conditions the 3D-2D transition was obtained after less than 7 nm of AlN growth. The surface roughness (rms) of a 100 nm thick AlN buffer layer was less than 1 nm. The full width at half maximum of the (0002) AlN peak was 2.9 arcmin. This is the best value reported so far for thin AlN layers on Si(111). The rapid transition to the 2D growth mode of AlN is essential for the subsequent growth of high quality GaN and AlGaN, and complete elimination of cracking in thick (>2 $\mu$m) GaN layers. For layers thicker than 1.5 $\mu$m, the width of the (0002) GaN diffraction peak was less than 14 arcsec. We show that a short period superlattice of AlGaN/GaN grown on the AlN buffer can be used to block the propagation of defects through GaN, resulting in excellent structural and optical properties. The AlN and GaN layers grown by MBE on Si were used as substrate materials for growth of thick (>100 $\mu$m) GaN layers by hydride vapor phase epitaxy. Structural and optical properties of thick GaN layers will be presented.

**4:45 PM W8.4**
MBE GROWTH OF NITRIDE-ARSENIDE MATERIALS FOR LONG WAVELENGTH OPTOELECTRONICS. S.G. Spruytte, C.W. Coldren, A.F. Marshall, J.S. Harris, Solid State and Photonics Laboratory, Stanford University, CA; M.C. Larson, Lawrence Livermore National Laboratory, CA.

Group III-Nitride-Arsenide is a promising material system for 1.3$\mu$m and 1.55$\mu$m optoelectronic devices applied in telecommunications. However, the growth of such nitride-arsenides is complicated by the difficulty of generating a nitrogen source and the divergent properties of nitride and arsenide materials. Growth of group III-Nitride-Arsenide materials was performed by elemental source molecular beam epitaxy employing a nitrogen r.f. plasma cell. The plasma conditions that maximize the amount of atomic nitrogen versus molecular nitrogen were determined using the emission spectrum of the plasma. The nitrogen concentration in the films is inversely proportional to the group III growth rate indicating that for our growth conditions all the supplied atomic nitrogen gets incorporated. TEM studies show that the InGaNAs quantum wells emitting at 1.3$\mu$m are sharp and defect-free. We have demonstrated edge emitting lasers. The key to pushing the emission to longer wavelengths is adding more nitrogen as this reduces the bandgap and allows increasing the indium content without the formation of misfit dislocations. However, the luminescence properties rapidly deteriorate with increasing nitrogen concentrations. As both the luminescence efficiency and crystal quality increase after annealing the InGaNAs quantum wells, it is possible that lattice defects associated with the incorporation of nitrogen cause deleterious non-radiative recombination. To verify this hypothesis, the nitrogen-bonding configuration was analyzed with XPS. The N(1s) spectrum indicates that the nitrogen exists in two configurations: a Ga-N bond and another N-complex in which N is less strongly bonded to Ga atoms.

SESSION W9: THEORY, DOPING
Chair: Randall M. Feenstra
Thursday Morning, December 2, 1999
Room 302 (H)

**8:30 AM *W9.1**
INDIUM AND Mg INDUCED CHANGES IN THE MORPHOLOGY

OF GaN(0001) GROWTH SURFACES. J.E. Northrup, Xerox Palo Alto Research Center, Palo Alto, CA.

Because of their use as the active region in blue light emitting diodes and lasers, there is wide interest in $In_xGa_{1-x}N$ alloys. A number of interesting phenomena have been observed in the course of studies of epitaxial $In_xGa_{1-x}N$ films including compositional fluctuations, chemical ordering, surfactant behavior and the formation of a novel defect, the so-called inverted hexagonal pyramid (IHP) defect. In this talk I will present first-principles calculations of the energetics of In on GaN surfaces. The results of these calculations are used to explain the formation of the IHP defects that terminate dislocations threading to the surface of the films. These defects are hexagonal shaped dislocation pits with sidewall facets consisting of six $(10\bar{1}1)$ facets. A model describing the formation energy of the IHP will be discussed. It will be shown that a significant driving force for the enlargement of the pit is the In-induced reduction in the $(10\bar{1}1)$ surface energy. This reduction in energy is traced to the existence of binding sites for the In surface atoms that exhibit only one or two bonds with underlying N atoms. It is preferable to occupy these sites with In atoms instead of Ga atoms. The innate difference between the In-N and Ga-N bonding that takes place on the $(10\bar{1}1)$ surface is also manifest at steps. I will discuss how *chemical ordering* on the group-III sublattice of InGaN may originate at steps during step flow growth of the film. If time permits, I will discuss the energetics and origin of Mg-induced c-plane inversion domain boundaries that have been observed during growth on GaN(0001) surfaces by Ramachandran *et al.*
This work was performed in collaboration with J. Neugebauer, L. Romano, V. Ramachandran, R. Feenstra, D. Greve, W. Sarney and L. Salamanca-Riba.

**9:00 AM *W9.2**
SPONTANEOUS POLARIZATION AND PIEZOELECTRIC FIELDS IN III-V NITRIDES NANOSTRUCTURES. Fabio Bernardini and Vincenzo Fiorentini, Istituto Nazionale per la Fisica della Materia and Dipartimento di Fisica, Universita di Cagliari, ITALY; Fabio Della Sala, Aldo Di Carlo and Paolo Lugli, Istituto Nazionale per la Fisica della Materia and Dipartimento di Ingegneria Elettronica, Università di Roma "Tor Vergata", ITALY.

Spontaneous (i.e. built-in) polarization is known to take place in semiconductors with sufficiently low crystal symmetry (e.g. ZnO and BeO). Its existence has been considered of purely theoretical interest since technologically relevant III-V's crystallize in the zincblende structure, whose symmetry is too high to allow the existence of spontaneous polarization fields. Recently a series of first principles calculations [1] have shown that III-V nitrides, whose natural crystal struture is wurtzite, own a very large spontaneous polarization, as well as larger-that-usual piezoelectric coupling constants. As a consequence of these anomalous polarization properties huge ($\sim$ 1–3 MV/cm) electric fields will appear in nanostructures like superlattices and MQW's. We show, for a large variety of nanostructure geometries and alloys compositions, how the values of the resulting electrostatic field can be predicted. Using a self-consistent tight-bindig approach we investigated the effects of such fields on the optical properties of MQW's[2]. [1] F. Bernardini, V. Fiorentini, and D. Vanderbilt, Phys. Rev. B 56, 10024 (1997); F. Bernardini and V. Fiorentini, Phys. Rev. B 57 9427 (1998). [2] F. Della Sala et al. Appl. Phys. Lett. 74, 2002.

**9:30 AM *W9.3**
GEOMETRIES AND ELECTRICAL PROPERTIES OF EXTENDED DEFECTS IN GaN. J. Elsner, A. Blumenau, Th. Frauenheim, Dept. of Physics, Univ. of Paderborn, Germany; R. Jones, Dept. of Physics, Univ. of Exeter, UK; M.I. Heggie, Dept. of Chemistry, Univ. of Sussex, UK.

We present the results of density–functional calculations for the geometries, energetics and electrical properties of extended defects in hexagonal and cubic GaN. In undoped and $p$–type material most of the extended defects in $\alpha$–GaN are found to be electrically inactive exhibiting only shallow gap states. However, in $n$–type material electrically active configurations can occur. In particular, oxygen impurities are found to segregate to the extended defects resulting in defect complexes with low formation energies and deep acceptor states. Moreover, we believe that oxygen is responsible for the formation of nanopipes in $\alpha$–GaN. We therefore investigate the incorporation of oxygen during growth along both the (0001) and $(000\bar{1})$ directions. Growth along the (0001) direction is found to build in less impurities.

**10:30 AM W9.4**
SIMULATION OF HYDROGEN MIGRATION AND REACTIONS IN GALLIUM NITRIDE. S.M. Myers, A.F. Wright, G.A. Petersen, W.R. Wampler, Sandia National Laboratories, Albuquerque, NM.

We developed a computer code that uses atomic-state energies to describe diffusion-related H behaviors in GaN including uptake, release, diffusion profiles, and the passivation and compensation of dopants. Account is taken of H0, H+, and H- undergoing interconversion and reaction with n- and p-type dopants and migrating under the influence of a depth-dependent Fermi level in the bandgap which is itself affected by the H. Objectives are to test mechanistic ideas and theoretical state energies through comparisons with experiment and to progress toward a quantitatively predictive description of H behavior. The code was implemented using ab-initio results obtained by one of us (Wright) and others for the ionization energies of H in solution, the formation energy of H2 in the lattice, the Mg-H binding energy, the diffusion activation energies of H, and the energy of H0 in solution relative to gaseous H2. Diffusion prefactors were equated to the representative interstitial value 0.001 cm2/s, and first-order approximations were made for H-related entropies. Distinct regimes of H transport were identified for H concentrations high enough relative to the dopant concentration to dominate the Fermi level, for concentrations too low to influence the Fermi level, and for intermediate concentrations where dopant compensation and passivation are significant. Detailed comparison was made with our experimental data for the diffusive release of H from implantation-formed H2 bubbles in n-type GaN at 700-900°C. Quantitative agreement was obtained for the magnitude and temperature dependence of the diffusion flux when the energy difference between gaseous H2 and lattice H0 was increased from a theoretical value of 2.6 eV to 2.8 eV. Our simulations of Mg-doped p-type material are generally consistent with published experimental information on the temperature range of dopant activation and the associated time-dependent depth profiles of H. Supported by Basic Energy Sciences, US DOE, under Contract DE-AC04-94AL85000.

**10:45 AM W9.5**
SURFACE SEGREGATION AND INTERFACE STABILITY IN AlN/GaN, GaN/InN, AND AlN/InN EPITAXIAL SYSTEMS. P. Bogusławski[1,2], K. Rapcewicz[1] and J. Bernholc[1]. [1]Department of Physics, NC State University, Raleigh, NC; [2]Instytut Fizyki PAN, Warsaw, POLAND.

Future semiconductor-based devices will rely on epitaxial growth of heterostructures controlled at almost the atomic scale. However, the profile of the chemical composition may differ substantially from the intentional one due to surface segregation or interdiffusion during post-growth annealing, which could lead to rough interfaces. We have studied theoretically these effects for III-nitride heterosystems using quantum molecular dynamics in a real-space implementation. Segregation energies have been calculated for AlN/GaN, GaN/InN and AlN/InN heterosystems in the wurtzite phase, for both the (0001) cation-polarity and the (000-1) nitrogen-polarity surfaces. In agreement with recent experiments we find that mixed AlGaN surfaces prefer Ga termination, and AlInN and GaInN surfaces prefer In termination. The calculated segregation energies for cation-rich conditions of growth are unexpectedly large, about 2-3 eV, which is an order of magnitude higher than in "classical" III-V and Si/Ge systems. This is due to the large differences in cohesive energies between AlN, GaN and InN, and a comparison with the energetics of interfaces reveals surface-specific effects that drive the segregation. However, the segregation effects on (0001) surfaces are strongly reduced in N-rich conditions, which suggests the usage of such conditions to suppress segregation. Further, both AlN/GaN and GaN/InN interfaces are only weakly unstable with respect to interdiffusion. Finally, we point out that by exploiting the strong pyro- and piezo-electric effects in the nitrides it may be possible to minimize the impact of the interface roughness on the lifetimes of free carriers confined in quantum wells.

**11:00 AM W9.6**
THE EFFECT OF INDIUM AT GaN SURFACES: AN ATOMIC PICTURE OF A SURFACTANT. Tosja K. Zywietz, Joerg Neugebauer, Matthias Scheffler, Fritz-Haber-Institut, Berlin, GERMANY.

Recent experimental investigations indicate that indium (In) may significantly improve the surface morphology and crystal quality of GaN-epilayers acting as a surfactant [1]. However, the microscopic mechanisms of how this is achieved are only poorly understood. Employing density-functional theory we have studied the effect of indium in detail: Analysing many different In-containing surfaces we find that submonolayers but also a complete monolayer of indium reduces the surface energy of GaN (0001) and $(000\bar{1})$ relative to the clean equilibrium surfaces. Based on the stable In-terminated surfaces the *kinetics* of Ga- and N-adatoms has been calculated: Depending on the structure, the diffusion barriers are either *decreased* or *increased* relative to the diffusion on the clean surface. Finally, the relevant exchange mechanisms (Ga against In, N against In) and the corresponding barriers have been studied. Based on these results we compare with experiments and discuss the consequences for the growth of GaN with and without In.
[1] F. Widmann *et al.*, Appl. Phys. Lett. **73**, 2642 (1998).

**11:15 AM W9.7**
Mg SEGREGATION, DIFFICULTIES OF P-DOPING IN GaN.
Z. Liliental-Weber, M. Benamara, W. Swider, and J. Washburn, Materials Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA; I. Grzegory and S. Porowski, High Pressure Research Center, Unipress, Polish Academy of Sciences, Warsaw, POLAND; R.D. Dupuis, Microelectronics Research Center, The University of Texas at Austin, Austin, TX.

Obtaining efficient p-type doping has been a continual challenge in GaN technology. Growth of platelet GaN doped with Mg from Ga solution under high hydrostatic pressure of Nitrogen does not ensure p-type conductivity despite a high concentration of Mg ($6x10^{19}$ $cm^{-3}$).Transmission electron microscopy shows formation of Mg rich defects but their atomic structure differs depending on crystal growth polarity. For growth with N-polarity spontaneous ordering of Mg rich planar defects is observed. These defects are monolayers of cubic structure formed on basal planes separated by 10 nm along c-axis. These defects introduce inversion in the crystals. No ordering is observed on the opposite side of the crystal (Ga to N polar direction), but three dimensional Mg-rich defects are formed. On this side of the crystals, the growth rate is an order of magnitude faster. Structure of Mg doped heterolayers with Mg delta doping and alternating GaN:Mg/GaN layers will also be studied in an attempt to determine under what conditions ordering and inversion are introduced.

**11:30 AM W9.8**
OPTICAL ACTIVATION BEHAVIOR OF ION IMPLANTED ACCEPTOR SPECIES IN GaN. G.L. Martinez, B.J. Skromme, Dept of Electrical Engineering and Center for Solid State Electronics, Arizona State Univ, Tempe, AZ.

Ion implantation permits the controlled introduction of any desired acceptor dopant in GaN without any passivating agents such as H. We have performed a low temperature photoluminescence (PL) investigation of several potentially important acceptors in GaN, by implanting C, Be, and Mg into high quality heteroepitaxial GaN grown by hydride VPE. Relatively low doses (averaging $10^{15}$, $10^{16}$, or $10^{17}$ $cm^{-3}$) are used to obtain high quality PL spectra. Multiple energy implants were used to produce approximately flat depth profiles, with the range adjusted to be the same for each ion. Rapid post-implantation thermal annealing was performed using reactively sputtered AlON encapsulation at 1300 °C for 8 s in a nitrogen ambient. Unimplanted control samples were also annealed and characterized. Dramatic, dose-dependent evidence of Mg acceptor activation was observed, including a strong, sharp (2.8 meV FWHM) neutral Mg acceptor-bound exciton and its characteristically strong LO phonon replica. The exciton localization energy is about 12 meV. Strong donor-acceptor pair peaks are observed, which shift to higher energy with increasing excitation intensity. Variable temperature measurements reveal a band-to-acceptor transition, whose energy yields an optical binding energy of 224 meV. Blue PL emission is observed at 2.35 eV. The Be implants yield no acceptor-bound exciton, and extremely weak donor-acceptor pair emission, in a stark contrast to Mg; the Be acceptor level is, however, somewhat shallower than Mg and its emission is less strongly phonon coupled. The C implants yield only very slight evidence of acceptor levels. Both Be and C implants produce dose-correlated yellow PL, tentatively attributed to residual implantation damage. The poor optical activation of Be and C may be related to insufficient vacancy production by these lighter ions; co-implantation experiments are planned to test this idea.

**11:45 AM W9.9**

Ga VACANCIES AND NEGATIVE IONS IN Mg DOPED GaN BULK CRYSTALS. K. Saarinen, J. Nissila, P. Hautojarvi, Laboratory of Physics, Helsinki University of Technology, FINLAND; J. Likonen, Technical Research Centre of Finland, FINLAND; T. Suski, I. Grzegory, B. Lucznik, S. Porowski, UNIPRESS, High Pressure Research Center, Polish Academy of Sciences, POLAND.

Nominally undoped GaN shows often heavily n-type conductivity with the concentration of electrons exceeding $10^{19} cm^{-3}$. This is most likely due to the residual oxygen atoms acting as shallow donors. Previous positron annihilation experiments [1,2] have shown that negative Ga vacancies are formed during the growth of such GaN bulk crystals and epitaxial layers. When GaN is doped with Mg or Be the electron concentration decreases and for sufficiently high amount of Mg dopants the samples become semi-insulating. A basic question concerns the origin of this effect. One can consider either (i) a gettering role of Mg leading to the formation of MgO or (ii) electrical compensation of O donors by Mg acceptors. In this work we apply positron annihilation spectroscopy to study the influence of Mg and Be doping on the Ga vacancy concentration in GaN crystals grown under 1.5 GPa nitrogen pressure at about 1500 °C. The Mg and O concentrations of the samples are determined experimentally by secondary ion mass spectrometry (SIMS), calibrated by implanting known amounts of impurities to undoped reference samples. The positron experiments show that the concentration of Ga vacancies decreases with increasing Mg concentration. When the Mg concentration exceeds the oxygen concentration, no Ga vacancies are observed. In Be doped GaN crystals the concentration of Ga vacancies is negligible. These trends are in good agreement with the theoretical calculations, which predict a low formation energy for the Ga vacancy and $V_{Ga}-O_N$ complex only in n-type material [3,4]. The positron lifetime experiments as a function of temperature indicate that negative ion defects trap positrons in addition to the Ga vacancies. The concentration of negative ions increases with Mg doping. Furthermore, the estimated concentrations are close to those of Mg impurities as determined by the SIMS measurement. Hence, we associate the negative ions as $Mg^{-}_{Ga}$. The positron results thus show that a substantial part of the Mg impurities is in negative charge state in Mg-doped GaN bulk crystals. This suggests that the conversion of n-type GaN to semi-insulating with Mg-doping is mainly due to an electrical compensation of oxygen donors with negatively charged Mg acceptors. The electrons originating from O donors are transferred to Mg acceptors charging them negatively. [1] K. Saarinen et al., Phys. Rev. Lett. 79, 3030 (1997). [2] K. Saarinen et al., Appl. Phys. Lett. 73, 3253 (1998). [3] J. Neugebauer and C.G. Van de Walle, Appl. Phys. Lett. 69, 503 (1996). [4] T. Mattila and R.M. Nieminen, Phys. Rev. B 55, 9571 (1997).

SESSION W10: CONTACTS, POINT DEFECTS, PROCESSING
Chair: Theodore Moustakas
Thursday Afternoon, December 2, 1999
Room 302 (H)

**1:30 PM *W10.1**
OHMIC CONTACTS TO p-GaN. Suzanne E. Mohney, Joon S. Kwak, Brett A. Hull, John M. DeLucca, Dept of Materials Science and Engineering, Penn State, University Park, PA; Hari S. Venugopalan, J.C. Ramer, Emcore Corporation, Somerset, NJ; Jung Han, Sandia National Laboratories, Albuquerque, NM.

Achieving low resistance ohmic contacts to p-GaN has presented a formidable challenge to the nitride community, and poor contacts have placed limitations on device performance. In the last year, however, numerous reports by us and other researchers have described improvements in these contacts, sometimes resulting in ohmic contacts with specific contact resistances in the $10^{-4}$ ohm-$cm^2$ range or better. Approaches to achieving reduced contact resistances include not only the selection of novel metallizations, but also the choice of the most appropriate method of metal deposition, optimization of the surface preparation procedure prior to deposition, and even annealing contacts in oxygen-containing environments. Due to variations in the ability to achieve low contact resistances on different samples of p-GaN, it can be difficult to make direct comparisons between the different metallization schemes described in the literature. Here we describe our experiences with the approaches described above, with comparisons made between different contacts fabricated on the same epilayers of p-GaN. We also report on our experiments designed to elucidate the mechanisms responsible for the improvements in the contacts fabricated by some of the new procedures.

**2:00 PM W10.2**
SELECTIVE AREA GROWTH AND IMPROVED P-CONTACTS TO GaN FOR BIPOLAR DEVICE APPLICATIONS. G. Simin, M. Asif Khan, J. Yang, A. Lunev, V. Chaturvedi, X. Hu, University of South Carolina, Dept. of ECE, Columbia, SC; M. Shur and R. Gaska, Rensselaer Polytechnic Institute, ECSE and CIEEM, Troy, NY.

Key problems in the development of GaN bipolar device technology include poor quality of p-layers and p-base contacts, resulting in high spreading resistance, and material degradation (especially, p-type layer) caused by mesa etching. In this paper, we report on development of selective area growth of GaN layers and greatly improved contact metallization schemes with contact resistance as low as $1x10^{-4}$Ohm.$cm^2$ at room temperature and $5x10^{-6}$ Ohm.$cm^2$ at 250 C. In particularly we demonstrate that using selective growth of top n-type layer in GaN n-p-n BJT allows us to avoid the processing degradation of a p-type layer. All the GaN layers for this study were grown on sapphire substrates using a standard low-pressure MOCVD process; Si- and Mg- were used as n- the p-dopants. For p-contact fabrication 0.2 $\mu$m thick p-GaN layer (hole concentration of $5x10^{17}$ $cm^{-3}$) were grown on a 1 $\mu$m thick n-layer. Our p-contact metal scheme consists of e-beam deposited Pd (50 A)/Au (100 A) layers. Post deposition, a 30-second RTA annealing at 400 C in oxygen ambient was used. TLM (Transmission Line Model) measurements were performed using 2 - 20 $\mu$m contact pad spacing. Contacts remained stable and linear up to 250 C. Note that at this temperature the carrier concentration in the p-GaN layer was measured to be

$1x10^{18}$ $cm^{-3}$. GaN n-p-n BJT structures were fabricated, with the top n-layer deposited only in selected areas ranging from 10x200 to 100x200 $\mu m^2$. Selectively regrown p-n junctions demonstrate turn-on voltage around 3 V in the temperature range 25 C to 300C. The leakage current varies from 15 $\mu$A at 25 C to 60 $\mu$A at 300C for 100x200 $\mu$m2 regrown n-layer area. Our initial results on bipolar junction transistor fabricated using improved p-contact metallization scheme and regrown n-layer demonstrate differential gain $\beta \approx 20$ at 300 C.

**2:15 PM W10.3**
OHMIC CONTACTS TO P-DOPED GaN/AlGaN SUPER-LATTICES. L. Zhou, A.T. Ping, F. Ahmed, A. Osinski*, I. Adesida, University of Illinois, Dept of Electrical and Computer Engineering, Urbana, IL; * NZ Applied Technologies, Woburn, MA.

High ohmic contact resistance and low bulk conductivity of p-type nitrides are among the major difficulties encountered in the development of nitride-based laser diodes and heterojunction bipolar transistors. In order to overcome these difficulties, methods must be found to increase the ionization efficiency of the deep Mg acceptor. One such method is to use GaN/AlGaN superlattices (SL). The use of a SL creates oscillations in the valence band-edge that when superimposed with the periodic oscillation generated by the piezoelectric field, would significantly reduce the Mg acceptor ionization energy and therefore increase the hole concentration. In this work, we demonstrate improved ohmic contacts to p-type GaN by using AlGaN/GaN SL. The hole concentration in the SL increased to 3-5E18 $cm^{-3}$. As a result, as-deposited Ti/Pt/Au contacts fabricated on a 20-period $Al_{0.1}Ga_{0.9}N$/GaN SL showed specific contact resistances of $\sim 6.5x10^{-4}$ $\Omega \cdot cm^2$, while a 20-period $Al_{0.2}Ga_{0.8}N$/GaN SL showed specific contact resistances of $\sim 4.0x10^{-4}$ $\Omega \cdot cm^2$. In contrast, the same metallization scheme showed Schottky behavior on p-GaN with nominal doping concentration of 2-3E17 $cm^{-3}$.

**2:30 PM W10.4**
FORMATION OF QUALITY Pt OHMIC CONTACTS TO P-TYPE GaN USING TWO-STEP SURFACE TREATMENT. Ja-Soon Jang, Han-Ki Kim, Seong-Ju Park, Tae-Yeon Seong, Department of Materials Science and Engineering, Kwangju Institute of Science and Technology (K-JIST), Kwangju, KOREA.

GaN and III-V nitride layers have been extensively investigated, since the realisation of short wavelength LEDs and LDs and the demonstration of metal-semiconductor field effect transistors and heterojunction bipolar transistors. Low resistance and thermally stable ohmic contacts are crucial for improving the performance of such devices. However, there are some obstacles, such as difficulty in increasing p-GaN near-surface carrier concentrations and the absence of metals having work function larger than that of p-GaN, which make it difficult to achieve low resistance ohmic contacts to p-GaN. In this work, we employ two-step surface-treatment to obtain low resistance Pt contacts to p-type GaN. The first step is performed after the mesa etching process using buffered oxide etch (BOE) and ammonium sulfide [$(NH_4)_2S_x$]. This is followed by the second step using BOE. The contact property is found to significantly depend on the surface-treated conditions. The Pt contact that was simply BOE-treated yields a specific contact resistance of $2.1x10^{-2}$ $\Omega cm^2$. However, the contact that was treated sequentially using BOE (10 min) and $(NH_4)_2S_x$ (10 min) produces $2.0x10^{-5}$ $\Omega cm^2$. To the best of our knowledge, this is the lowest contact resistance reported hitherto for the contacts on p-GaN, indicating that the two-step surface treatment is promising technique for obtaining high quality ohmic contacts to p-GaN. The effective Schottky barrier heights (SBHs) of the differently surface-treated contacts are determined using the Norde and current-voltage methods. It is shown that the SBHs are dependent upon the surface-treated conditions. Post-deposition annealing treatment is also performed to investigate the electrical and thermal stability of the not-treated and surface-treated contact schemes. Effects of annealing temperature on the contact properties are described and discussed.

**3:15 PM *W10.5**
ELECTRICAL MEASUREMENTS IN GaN: POINT DEFECTS AND DISLOCATIONS. David C. Look, Wright State University, Semiconductor Research Center, Dayton, OH.

Defects, both point defects and line defects (dislocations), can act as donors, acceptors, traps, and recombination centers in semiconductor materials. For example, in n-type GaN, it has been clearly shown that threading dislocations are acceptor-like, and, at typical concentrations, will severely affect mobility. On the other hand, less is understood about point defects, although there is good evidence that at least one of them, the nitrogen vacancy ($V_N$), exists as an electron trap in MBE-grown GaN, and probably also in MOCVD and HVPE material. In this talk, we show how temperature-dependent Hall-effect (TDH) measurements and deep level transient spectroscopy (DLTS) can be used to quantitatively study the effects of point and line defects. The identification of the various point defects is facilitated by high-energy electron-irradiation experiments, and, so far, electrical and/or optical "fingerprints" have been proposed for $V_N$ and the Ga interstitial ($Ga_I$); however, it must be pointed out that this research area is still in it's infancy, with the first papers appearing only two years ago. In highly-doped n-type GaN, the Ga vacancy has been identified by positron annihilation experiments, and the dominant donor is thought to be either $V_N$ or $O_N$. However, by a TDH analysis of electron-irradiated GaN, it can be shown that the dominant donor in the "best" (say, $10^{17}$-$cm^{-3}$) as-grown material, is not $V_N$, but is probably $O_N$ or $Si_{Ga}$. The DLTS results show that at least two defects are produced by 1-MeV electrons, but both are believed to be related to $V_N$. Some of the other traps, in as-grown material, have features suggesting the involvement of dislocations. Thus, point defects and dislocations produce donors, acceptors, and traps in GaN, and are likely to be important in the further development of both electronic and photonic devices.

**3:45 PM *W10.6**
PROPERTIES AND EFFECTS OF HYDROGEN IN GaN. S.J. Pearton, Dept. Materials Scinece and Engineering, University of Florida, Gainesville, FL.

The passivation of Mg acceptors in GaN by residual atomic hydrogen from the growth precursors (TMGa, $NH_3$, $H_2$ carrier gas) is well established, but the reactivation of the Mg and removal of hydrogen from the GaN are often the subject of confusion. Moreover, the role of hydrogen during the growth process itself is not well established, with claims of higher Mg acceptor incorporation efficiency or passivation of residual defects in MOCVD-grown material relative to the (usually) $H_2$-free growth ambient of MBE. The evidence for all these effects will be critically evaluated, and contrasted with what is known about hydrogen in other compound semiconductor systems.

**4:15 PM W10.7**
LATTICE LOCATION OF DEUTERIUM IN PLASMA CHARGED Mg DOPED GaN. W.R. Wampler and J.C. Barbour, Sandia National Laboratories, Albuquerque, NM.

Ion channeling provides a unique and direct way to determine the location of solute atoms relative to the host lattice. We have used ion channeling to examine the atomic configuration of deuterium in Mg doped GaN. The material used was wurtzite GaN grown by MOCVD, doped with 5E19/$cm^3$ Mg. The GaN was exposed at 600°C to a deuterium (D) ECR plasma. SIMS depth profiles showed about one D per Mg atom in the doped GaN after the D plasma exposure. The yield of protons from the 3He(D,P)4He nuclear reaction was measured versus angle between the analysis beam and the [0001] crystallographic axis. A broad dip in yield was observed whose width was similar to that of the host lattice backscattering yield. Comparison with channeling simulations for various D locations show the dip in yield is due to D in line with GaN atom rows along the c-axis. Published calculations for cubic GaN predict that H is strongly bound at anti-bonding sites of nitrogen atoms adjacent to Mg. In the hexagonal wurtzite lattice the N-antibonding site in the (0001) direction differs from the other three N-antibonding sites. Our channeling results are consistent with preferred occupation of the N-antibonding site in the (0001) direction. Supported by Basic Energy Sciences, US DOE, under contract DE-AC04-94AL85000.

**4:30 PM W10.8**
SURFACE CONVERSION EFFECTS IN PLASMA DAMAGED p-GaN. X.A. Cao, S.J. Pearton, University of Florida, Department of Materials Science and Engineering, Gainesville, FL; G.T. Dang, A.P. Zhang, F. Ren, University of Florida, Department of Chemical Engineering, Gainesville, FL; R.J. Shul, L. Zhang, Sandia National Laboratories, Albuquerque, NM; R. Hickman and J.M. Van Hove, Blue Lotus Micro Devices, Eden Prairie, MN.

The reverse breakdown voltage of p-GaN Schottky diodes was used to measure the electrical effects of high density ICP Ar or $H_2$ plasma exposure. The near-surface of the p-GaN became more compensated through introduction of shallow donor states whose concentration depended on ion flux, ion energy and ion mass. At high fluxes or energies, the donor concentration exceeded $10^{19}$ $cm^{-3}$ and produced p-to-n surface conversion. Both the depth-dependence of wet chemical etching rate and breakdown voltage of diode structures were used to establish the damage profile in the plasma-exposed GaN. The electrical (and wet etching) properties were returned to their control values after removal of $\sim 400$ $\AA$ of the surface. The plasma-induced damage was removed by 900 °C annealing under a $N_2$ ambient, similar to the thermal stability of implant-isolated p-GaN.

**4:45 PM W10.9**

ZIRCONIUM MEDIATED HYDROGEN OUTDIFFUSION FROM p-GaN. E. Kaminska, A. Piotrowska, A. Barcz, Institute of Electron

Technology, Warsaw, POLAND; J. Jasinski, Institute of Experimental Physics, Warsaw University, POLAND; M. Zielinski, Institute of Physics PAS, Warsaw, POLAND; R.F. Davis, NCSU, Raleigh, NC; M.D. Bremser, Aixtron, Inc., Buffalo Grove, IL; E. Goldys, K. Tomsia, SMPCE, Macquarie University, Sydney NSW, AUSTRALIA.

Recent interest in GaN-based devices has stimulated studies on p-type doping issues[1] as well as the search for novel ohmic contacts[2]. The role of hydrogen in the passivation and activation of dopants in MOCVD grown material is recognized, nevertheless its behavior is not fully understood. The present study addresses the problem of the possible removal of hydrogen from the near-surface region in p-type GaN. The accumulation of hydrogen in areas of high defect density has been recently postulated[3]. It is therefore very likely that hydrogen could be accumulated at the surface of p-GaN. As a consequence, the subsurface volume may contain a lower free carrier concentration than the bulk. We have studied this problem using p-GaN:Mg grown on SiC or on sapphire. To facilitate the evolution of hydrogen the surface of p-GaN has been metallized with sputter-deposited Zr-N or Zr-B films. Zirconium possesses one of the highest absorptive capabilities for hydrogen of metal hydride systems, while ZrN and $ZrB_2$ are distinguished for their exceptional low resistivities and high melting points. Hydrogen depth profiling was performed using a Cameca 6F SIMS. The thermal stability of Zr-based caps on GaN has been investigated using TEM. The electrical characterization of metal/p-GaN systems involved measurements of I-V characteristics and resistivity of ohmic contacts. Our results prove a significant accumulation of hydrogen in the subsurface region and its measurable level in the bulk of p-type GaN. After thermal processing at temperatures above 800°C the release of hydrogen from p-GaN via Zr-based cap is observed. The system remains stable even after processing at 1150°C. No hydrogen was detected in caps after annealing. Removal of hydrogen was found to promote the formation of ohmic contacts. [1]C.G. Van de Walle, N.M.Johnson, Semiconductors and Semimetals, 57, 157 (1999) [2]M. Murakami, Y. Koide, Critical Rev. Sol. State Mat., 23, 1 (1998) [3]S.J. Pearton et al., J. Vac. Sci. Technol. A, 14, 831 (1996).

SESSION W11: POSTER SESSION:
DEVICES, OPTICAL CHARACTERIZATION,
PROCESSING, CONTACTS, DEFECTS
Chairs: Hiroshi Amano, Randall M. Feenstra,
Thomas H. Myers and Michael S. Shur
Thursday Evening, December 2, 1999
8:00 P.M.
Exhibition Hall D (H)

**W11.1**
P-I-N GaN DIODES FABRICATED ON HVPE AND ELO-HVPE SUBSTRATES. A.V. Sampath, Y. Fedyunin, H.M. Ng, M. Misra, E. Iliopoulos, Z. Feit, T.D.Moustakas, Photonics Center, Boston University, Boston, MA.

Recently there has been great interest in fabricating GaN based solar blind UV photodetectors. These devices promise to have improved radiation hardness, considerable visible light rejection and operability at elevated temperatures. However, these devices have large reverse bias leakage current that is presently attributed to the large density of dislocations existing in MBE and MOCVD grown GaN. In contrast, thick GaN substrates grown by HVPE (Hydride Vapor Phase Epitaxy), or ELO (Epitaxial Lateral Overgrowth) methods have been shown to have a greatly reduced dislocation densities. In this paper we report on the fabrication of p-i-n GaN diodes grown by MBE on HVPE and ELO HVPE substrates. The MBE grown active layer consists of a .5 micron thick p- layer and a 1 micron thick i- layer. Circular diodes with a diameter of 300 microns were fabricated. These devices were characterized by I-V-T and C-V measurements. Reverse leakage currents as low as $6x10^{-6}$ A/cm$^2$ were measured at ~10 V.

**W11.2**
VERTICAL TRANSPORT PROPERTIES OF GaN SCHOTTKY DIODES GROWN BY MOLECULAR BEAM EPITAXY. M. Misra, A.V. Sampath and T.D. Moustakas Department of Electrical and Computer Engineering and Center for Photonics Research, Boston University, Boston MA.

The mobility of electrons in GaN for transport in the lateral direction is known to be reduced due to scattering by dislocations 1,2. We report, for the first time, the measurement of electron mobility for transport in the vertical direction, which has important implications for many devices, including lasers, transistors and detectors. Schottky barrier diodes with a vertical geometry were fabricated on GaN n+/n- layers grown by ECR-MBE. Ni/Pt/Au multi-layers were deposited to form the Schottky contact at the top of the mesa and Ti/Al/Ni/Au layers were deposited to form the bottom Ohmic contact. The diodes were characterized by I-V, I-V-T and C-V measurements. Relevant parameters such as the ideality factor, doping concentration, barrier height and Richardson constant were determined. The barrier height was determined to be 1.03eV by both I-V-T and C-V measurements. From the measurement of the saturation current, the mobility was calculated, using the diffusion model of current transport in Schottky barriers. For typical saturation current density of J0= 7x10-10A/cm2, the mobility was calculated to be 1.03x103 cm2/V-s. This is about 20 times greater than the lateral mobility measured for an n- layer grown under identical conditions. We attribute the higher mobility in the vertical structure to absence of scattering of electrons by dislocations during vertical transport. In addition, the diodes were evaluated as photodetectors. They exhibited a responsivity of 0.2A/W at 325nm, corresponding to quantum efficiency of 70%. Noise measurements indicate 1/f noise to be the dominant source of noise in these detectors.

**W11.3**
PULSED LASER DEPOSITED AlN FILMS FOR HIGH-TEMPERATURE SiC MIS DEVICES. R.D. Vispute, A. Patel, Kathleen Baynes, Bin Ming, R.P. Sharma and T. Venkatesan, CSR, Department of Physics, University of Maryland, College Park, MD.; C.J. Scozzie, A. Lelis, T. Zheleva and K.A. Jones, U. S. Army Research Laboratory, Adelphi, MD.

The most significant task in the high temperature electronics based on SiC and GaN is the fabrication of high quality dielectrics. Thin films of AlN seem to be promising as a dielectric as compared to $SiO_2$ for metal-insulator-semiconductor (MIS) structures. The other advantage of AlN/SiC materials system is the small lattice mismatch between AlN and SiC. In this context, we report on the development of high-quality AlN heterostructures grown on SiC for high-temperature electronic devices. The AlN films were grown by pulsed laser deposition (PLD)[1] at substrate temperatures ranging from 25C (room temperature) to 950C. The AlN films grown above 600C were highly c-axis oriented with rocking curve FWHM of 5 to 6 arcmin. The ion channeling minimum yields near the surface region for the AlN films were ~ 2 to 4% indicating their high degree of crystallinity. The surface roughness for the films was about the 0.5 nm which is close to the unit cell height of the AlN. Epitaxial TiN and Pt/TiN ohmic contacts were also developed on SiC, GaN and AlN by in-situ PLD. Epitaxial TiN/AlN/SiC MIS capacitors with gate areas of $4x10^{-4}$ cm$^2$ were fabricated, and high temperature current-voltage (I-V) characteristics were studied up to 450C. We have measured leakage current densities of low $10^{-8}$ A/cm$^2$ at room temperature and of mid $10^{-3}$ A/cm$^2$ at 450C under 2 MV/cm field[2]. The issues related to the electrical properties as a function of crystallinity, film thickness, nitrogen content, and the defects will also be discussed. [1] R.D. Vispute, S. Choopun, R. Enck, A. Patel, V. Talyansky, R.P. Sharma, T. Venkatesan, W.L. Sarney, L. Salamanca-Riba, S.N. Andronescu and A.A. Iliadis, K.A. Jones, J. Electronic Materials, 28, 275 (1999). [2] C.J. Scozzie, A.J. Lelis, B.F. McLean, R.D. Vispute, A. Patel, R.P. Sharma, and T. Venkatesan, Appl. Phys. Lett. (Submitted).

**W11.4**
GaP-DEVICES FOR HIGH TEMPERATURE APPLICATIONS. Yu. V. Zhilyaev, E.A. Panyutin, L.M. Fedorov, A.F. Ioffe Physico-Technical Institute, St. Petersburg, RUSSIA.

The results on high temperature diodes, stabilizer diodes, diode thyristors (vertical technology) as well as JFET's operating at 400-450°C are reported. Epitaxial structures for all device types were prepared with the use by the same technology - gas phase epitaxy in the open tube chloride system and in the same reactor; they differed in the number of layers, their thickness and doping features. The distinguishing feature of these processes is the use of a combination Mg-Zn doping, with the component ratio controlled depending on the p-layer growth rate; this technology drastically reduced the negative effect of residual dislocations whose concentration at the surface of a 20-/$mu$m buffer layer amounted to $10^4$ cm$^2$. It is presumed that the difference in the covalent radius of Zn and Mg precludes the autodiffusion of zinc into n and no layers during growth of the p-layer. The resulting considerable improvement in the uniformity of the bound charge spatial distribution made it possible to produce dc stabilizer diodes for voltages from 15 to 80 V, improve forward IV characteristics of high-voltage diodes without lowering of the maximum reverse voltage (300V), and shrink the transconductance spread in 8x8 transistor matrices to values below 20%. It is assumed that further studies of binary and multi-component doping can produce (due to local changes of the deformation potential) conditions for reducing the total concentration of deep levels introduced by intrinsic defects which are controlled by residual growth dislocations.

**W11.5**
ELECTRIC PROPERTIES OF METAL-FERROELECTRIC-GaN STRUCTURES. W.P. Li, R. Zhang, Y.G. Zhou, J. Yin, H.M. Bu, Z.Y. Luo, B. Shen, Y. Shi, R.L. Jiang, S.L. Gu, Z.G. Liu, Y.D. Zheng, Department of Physics and National Laboratry of Solid State

Microstructure Nanjing University, Nanjing, CHINA; Z.C. Huang Raytheon ITSS, Baltimore, MD.

GaN-based meatal-ferroelctric-semiconductor (MFS) structure has been fabricated by using ferroelectric $Pb(Zr_{0.53}Ti_{0.47})O_3$ (PZT) instead of conventional oxides as insulator gate. The Electric properties of GaN MFS structure are characterized by high-frequency C-V method and radiant Technologies Pulsed Testing System (RT6000HVS).The current leakage of PZT deposited on GaN is as low as 10-11 A The polarization of PZT under 5V bias is about 4.7E-6 $C/cm^2$. Because of the polarization field provided by ferroelectric and the high dielectric constant of ferroelectric insulator, the capacitance-voltage (C-V) characteristics of GaN-based metal-ferroelectric-semiconductor (MFS) structures are markedly improved compared to that of other previously studied GaN MIS structures. The GaN surface layer in MFS structures can reach inversion just under the bias of smaller than 5 volts, which is the generally applied voltage used in semiconductor-based integrated circuits. The carrier concentration of GaN surface layer in MFS structure is decreased by one order compared with the background carrier concentration of GaN. These results show GaN MFS structure is a promising MIS structure for applications.

**W11.6**
GROWTH AND CHARACTERIZATION OF III-V NITRIDE TRANSISTORS FOR HIGH-POWER ELECTRONICS. C.J. Eiting, D.J.H. Lambert, H.K. Kwon, B.S. Shelton, M.M. Wong, T.G. Zhu and Russell D. Dupuis, The University of Texas at Austin, Microelectronics Research Center, Austin, TX; and Z. Liliental-Weber, J. Mazur and M. Benamara, Lawrence Berkeley National Laboratory, Berkeley, CA.

We report the growth and characterization of high-quality AlGaN/GaN heterojunctions by low-pressure metalorganic chemical vapor deposition (MOCVD) in hydrogen with trimethylgallium (TMGa), trimethylaluminum (TMAl), silane (SiH4), and ammonia (NH3) precursors. We have varied the growth conditions (e.g., growth temperature, V/III ratio, growth pressure) and have studied the correlation of the symmetric and asymmetric X-ray diffraction linewidths, surface morphology, and modulation doping concentrations upon the mobility and sheet charge density of the two-dimensional electron gas (2DEG). AlGaN films with various alloy compositions have been used as the wide-bandgap layer in these structures. Some samples employed entirely undoped 2DEG structures while others contained modulation-doped heterostructures with various set-back layer thicknesses. We find that the 2DEG mobility is highly dependent on the growth conditions employed at the transition from GaN to AlGaN growth. Specifically, inserting a short NH3/H2 purge step just before AlGaN deposition results in improved mobility heterostructures relative to continuous growth or a long purge. This purge presumably sweeps out leftover TMGa and promotes stoichiometric two-dimensional growth of AlGaN. Contrary to what is commonly reported for bulk GaN/sapphire epitaxial layers, preliminary 300K electrical data from these 2DEG films show no strong correlation between asymmetric (102) X-ray rocking curve FWHM values for the GaN layer and the electron mobility in the 2DEG. Such behavior might be expected if the electrons are confined to the two-dimensional layer at the AlGaN/GaN interface and thus the mobility is not strongly dependent on bulk properties. Surface atomic-force microscopy (AFM) measurements on 5x5 mm areas show RMS roughness values between 0.5 and 1.0 nm independent of the measured mobility. Electron sheet charge density in these heterostructures correlates well with mobility, higher sheet concentrations resulting in lower mobilities. Low-temperature PL studies have established the increased concentration of electrons in the 2 DEG, consistent with the electrical data.

**W11.7**
HIGH MOBILITY TWO-DIMENSIONAL ELECTRON GAS IN AlGaN/GaN HETEROSTRUCTURES GROWN BY PLASMA-ASSISTED MOLECULAR BEAM EPITAXY. C.R. Elsass, I.P. Smorchkova, B. Heying, E. Haus, P. Fini, K. Maranowski, J.P. Ibbetson, S. Keller P.M. Petroff, S.P. DenBaars, U.K. Mishra, J. S. Speck, University of California, Materials and Electrical Engineering, Santa Barbara, CA.

There have been numerous reports on high quality AlGaN/GaN heterostructures grown by MOCVD with electron mobilitites as high as 2050 $cm^2/Vs$ and 9000 $cm^2/Vs$ (carrier density $1x10^{13}$ $cm^{-2}$) at 300K and 77K, espectively (Gaska et. al., APL, 1999). Two-dimensional electron gas (2DEG) AlGaN/GaN structures have also been realized by molecular beam epitaxy (Li, et. al., J. Vac. Sci. Tech. B, 1998), however until recently their transport characteristics have been inferior to those grown by MOCVD. UCSB MOCVD GaN (0001) n-type templates nucleated on sapphire were used for the MBE AlGaN/GaN growth. Unintentionally doped MBE GaN was grown at 750C on the template followed by AlGaN with a nominal thickness of 250 nm and 50 nm respectively. Temperature dependent Hall measurements showed a room temperature mobility of 1150 $cm^2/Vs$, 77K mobility of 14,500 $cm^2/Vs$, increasing to 20,000 $cm^2/Vs$ at 12K. The sheet carrier concentration varied from $1.4x10^{13}$ $cm^{-2}$ at room temperature to $4.8x10^{12}$ $cm^{-2}$ at 12K. Because the sample was grown on n-type MOCVD GaN a parallel conduction path of low mobility carriers exist and significantly affects the room temperature measurements. The magnetic field dependence of the longitudinal resistance of the $Al_{.07}Ga_{.93}N$/GaN heterostructure at 4.2K showed Shubnikov-de Haas oscillations starting at about 2.5 Tesla confirming the presence of a 2DEG at the $Al_{.09}Ga_{.91}N$/GaN heterointerface. By optimizing the heterostructure a 12K mobility of 50,000 $cm^2/Vs$ was achieved. The high quality of the 2DEG may be due to a number of factors. The AlGaN/GaN interface of the MBE films may have less roughness than corresponding MOCVD films. Fewer impurities in the MBE grown film compared to MOCVD grown films could also be the reason for increased mobility.

**W11.8**
GROWTH AND CHARACTERIZATION OF PIEZOELECTRICALLY ENHANCED P-TYPE AlGaN/GaN HETEROSTRUCTURES. A. Michel, Dept of Chemical Engineering, D. Hanser, R.F. Davis, Dept Materials Science and Engineering, North Carolina State University, Raleigh, NC; D. Qiao, S.S. Lau, L.S. Yu, W. Sun, P. Asbeck, Electrical and Computer Engineering Department, University of California San Diego, LaJolla, CA.

Gallium nitride-based high-mobility bipolar transistors (HBT) are promising power devices for compact, efficient power supplies. A key issue in the development of nitride-based HBTs is a more conductive base layer. Conventional p-type GaN thin films are too resistive due to problems with Mg doping including formation of Mg-H complexes and native defect compensation. Thin films of Mg-doped GaN and AlGaN/GaN heterostructures were grown in an MOVPE reactor at 45 Torr and 1000oC. Graded AlGaN and GaN epilayers were doped with Mg from a metalorganic magnesium source, and the films were subsequently annealed at 800oC in nitrogen. It has been demonstrated that piezoelectric effects from AlGaN/GaN heterostructures significantly contribute conductivity in the base material relative to conventional Mg-doping. Hall measurements were performed on the heterostructures to determine the effect of piezolelectric doping on mobility and conductivity of the material. The sheet conductance of the film that incorporates piezoelectric effects along with Mg-doping exhibited a sheet conductance of 20-$\mu$S compared to Mg-doped GaN that exhibited a conductance of 7-$\mu$S. The results of analyses of the Mg-doping levels and the AlGaN/GaN interface via SIMS and depth-profile AES, respectively, will be reported and correlated with the electrical data.

**W11.9**
LOW-FREQUENCY NOISE IN AlGaN/GaN HETEROSTRUCTURES ON SiC AND SAPPHIRE SUBSTRATES. N. Pala[1], R. Gaska[1], M. Shur[1], J.W Yang[2] and M. Asif Khan[2]; [1]Department of ECSE, Rensselaer Polytechnic Institute, Troy, NY, [2]Department of ECE, University of South Carolina, Columbia, SC.

We report a comparative study of the low-frequency noise in AlGaN/GaN heterostructures with 2D electron gas grown on sapphire and conducting 6H-SiC substrates by low-pressure MOCVD. The investigated samples with TLM patterns had nearly the same electron sheet density and the Hall mobility close to $9x10^{12}$ $cm^{-2}$ and 1,000 $cm^2/Vs$, respectively. The results showed that for both types of the substrates the Noise Spectral Density (NSD) at zero gate bias was nearly the same and decreased with increasing the spacing between the TLM contacts. We link this decrease in NSD with the increase in a total number of carriers in the 2D channel. The NSD exhibited strong dependence on applied gate bias, $V_g$. The noise in the samples with 100 nm thick $SiO_2$ layer between AlGaN barrier and the gate electrode decreased monotonously with increase in $V_g$ from -18 V up to 4 V. We attribute this effect to the increase in the sheet electron density in the channel, which is in good agreement with the noise theory. In contrast, NSD in heterostructures without the isolating $SiO_2$ layer sharply increased for both positive and negative gate bias because of the gate leakage. We also measured the NSD dependence on sheet electron density in the heterostructures grown on 6H-SiC using the conducting substrate as a back-gate. This allowed us to modulate the electron density in 2D gas at AlGaN/GaN heterointerface. The obtained results demonstrated that the back bias may reduce NSD by more than order of magnitude. The level of noise in these structures is comparable to that for GaAs MESFET, which is good indication of high material quality and expected reliability of AlGaN/GaN heterostructure technology.

**W11.10**
CHARACTERIZATON OF AN AlGaN/GaN TWO-DIMENSIONAL ELECTRON GAS STRUCTURE. A. Saxler, P. Debray, R. Perrin, S. Elhamri and W.C. Mitchel, Air Force Research Laboratory, Materials

and Manufacturing Directorate, AFRL/MLPO, Wright-Patterson AFB, OH; C.R. Elsass, I.P. Smorchkova B. Heying, E. Haus, P. Fini, J.P. Ibbetson, S. Keller, P.M. Petroff, S.P. DenBaars, U.K. Mishra and J.S. Speck, College of Engineering, University of California, Santa Barbara, CA.

An $Al_xGa_{1-x}N$/GaN two-dimensional electron gas structure with x=0.13 was deposited by molecular beam epitaxy on a GaN layer grown by organometallic vapor phase epitaxy on a sapphire substrate. The electron effective mass was determined to be 0.22 based on the temperature dependence of the amplitude of the Shubnikov-de Haas oscillations. The quantum lifetime was substantially lower than the transport lifetime of 2.3 x $10^{-12}$ s which is based on a mobility of 1.9 x $10^4$ $cm^2$/Vs measured by the Hall effect. The sheet carrier concentrations determined by Hall and Shubnikov-de Haas were in good agreement at 5x$10^{-12}$ $cm^{-2}$ indicating absence of parallel conduction. Magnetic field dependent Hall effect analysis also showed negligible parallel conduction at low temperatures. X-ray diffraction maps of asymmetric reciprocal lattice points confirmed that the thin AlGaN layer was coherently strained to the thick GaN layer. Methods for computing the aluminum mole fraction in the AlGaN layer by x-ray diffraction are discussed.

**W11.11**
COMPARISON OF SPONTANEOUSLY INDUCED CARRIERS IN HEXAGONAL AND CUBIC AlGaN/GaN UNDOPED HETERO-STRUCTURES. Michael J. Manfra, Loren N. Pfeiffer, Denis Buchanan, K.W. West, Bell Labs, Lucent Technologies, Murray Hill, NJ.

In the last 2 years it has become clear that spontaneous and piezoelectric polarization fields drastically alter the charge distribution at AlGaN/GaN interfaces. Hexagonal, or wurtize, GaN lacks inversion symmetry along the growth direction. This results in a large built-in electric field at the AlGaN/GaN interface which has been used by several groups to form a two-dimensional electron gas without the need of Silicon modulation doping. Because the underlying crystal symmetry plays a crucial role in the determination of spontaneous and piezoelectric polarization fields in AlGaN/GaN heterostructures, it is expected that zinc-blende GaN heterostructures grown along the (100) cubic axis should not support such spontaneous polarization fields and may prove useful for quantum structures in which unwanted free carriers prove detrimental. We report on the characterization and comparison of cubic and hexagonal AlGaN/GaN heterojunctions grown by plasma nitrogen molecular beam epitaxy. Cubic structures were grown using the (100) face of GaAs as an epitaxial template. The structure consists of 500nm of GaN capped with 40nm of $Al_{0.2}Ga_{0.8}N$. The hexagonal structures grown on (0001) sapphire substrates were identical to the cubic structures except for the use of an AlN nucleation layer to insure Ga-polar material. In order to assess the phase purity and material quality of our structures we have employed a variety of characterization techniques including X-ray reciprocal space mapping, Raman spectroscopy, atomic force microscopy (AFM), transmission electron microscopy (TEM), and low temperature Hall measurements. Our data confirm that hexagonal heterostructures do result in the spontaneous formation of a two dimensional electron gas, whereas preliminary results on cubic AlGaN/GaN heterostructures of comparable quality appear to show no such spontaneous polarization effects.

**W11.12**
OPTIMIZATION OF AlGaN/GaN HETEROJUNCTION FIELD EFFECT TRANSITOR STRUCTURES BY USING PERSISTENT PHOTOCONDUCTIVITY AS A PROBE. J.Z. Li, J. Li, J.Y. Lin, and H.X. Jiang, Department of Physics, Kansas State University, Manhattan, KS.

High quality $Al_{0.2}Ga_{0.8}N$/GaN heterojunction field effect transistor (HFET) structures grown on sapphire substrates with high sheet carrier density and mobility products ($n_s\mu$=1.4 x $10^{16}$/Vs at room temperature) have been produced by metal organic chemical vapor deposition (MOCVD). The optimized structures were achieved by varying structural parameters, including the intrinsic AlGaN spacer layer and the Si-doped AlGaN layer thicknesses and the Si-doping concentration. In these structures, the persistent photoconductivity (PPC) effect associated with the two-dimensional electron gas (2DEG) system was invariantly observed. As a consequence, the characteristic parameters of the 2DEG were sensitive to light and the sensitivity was associated with permanent photoinduced increases in the 2DEG carrier mobility and sheet carrier density. However, we observed that the magnitude of the PPC and hence the photoinduced instability associated with these heterostructures were a strong function of only one parameter, the product of $n_s$ and $\mu$, which is the most important parameter for HFET device applications. For a fixed excitation photon dose (excitation intensity x excitation time), the ratio of the low temperature PPC to the dark conductivity level was observed to decrease from 200% to 3% as the nsl (300 K) product was increased from 0.048 x $10^{16}$/Vs to 1.4 x $10^{16}$/Vs. Based on our studies, we suggest that the magnitude of the low temperature PPC can be used as a sensitive probe for monitoring the electronic quality of the AlGaN/GaN HFET structures.

**W11.13**
FULL BAND MONTE CARLO COMPARISON OF WURTZITE AND ZINCBLENDE PHASE GaN MESFETS. Maziar Farahmand and Kevin F. Brennan, School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA.

The output characteristics, cutoff frequency, breakdown voltage and the transconductance of wurtzite and zincblende phase GaN MESFETs have been calculated using a self-consistent, full band Monte Carlo simulation. It is found that the calculated breakdown voltage for the wurtzite device is considerably higher than that calculated for a comparable GaN zincblende phase device. One the other hand, the zincblende device is calculated to have a higher transconductance and cutoff frequency than the wurtzite device. The higher breakdown voltage of the wurtzite phase device is attributed to the higher density of electronic states for this phase compared to the zincblende phase. The higher cutoff frequency and transconductance of the zincblende phase device is attributed to more appreciable electron velocity overshoot for this phase compared to that for the wurtzite phase. The maximum cutoff frequency and transconductance of a 0.1 $\mu$m gate-length zincblende phase GaN MESFET are calculated to be 220GHz and 210 mS/mm, respectively. The corresponding quantities for the wurtzite phase GaN device are calculated to be 160GHz and 158 mS/mm, respectively.

**W11.14**
AlGaN THICKNESS DEPENDENCE OF MOBILITY AND DENSITY OF TWO DIMENSIONAL ELECTRON GAS IN MODULATION DOPED AlGaN/GaN HETEROSTRUCTURES. Bo Shen, Takao Someya, Masao Nishioka, Yasuhiko Arakawa, Institute of Industrial Science, Univ. of Tokyo, JAPAN.

Several reports indicate that the piezoelectric polarization of the AlGaN barrier is one of the main factors to determine the transport properties of two dimensional electron gas (2DEG) in an AlGaN/GaN heterostructure. The piezoelectric polarization is influenced significantly by the elastic strain relaxation of AlGaN on GaN. However, the relaxation mechanism of AlGaN on GaN is not clear yet. There is a large difference of the AlGaN critical thickness on GaN between the experiment result and the theoretical calculation. Since the relaxation of an AlGaN layer on GaN is determined by the thickness of the AlGaN layer, the influences of the thickness of Si-doped n-type AlGaN barrier and the thickness of the AlGaN spacer on the mobility and the density of 2DEG in modulation doped AlGaN/GaN heterostructures were investigated in this study. The samples were grown by atmospheric pressure metal organic chemical vapor deposition. The Al molar fraction in the AlGaN barrier is 0.15. The mobility and the density of 2DEG were measured by means of Van der Pauw Hall measurements at various temperatures between 10 K and 300 K. 2DEG mobilities of 1274 $cm^2$/V.s at 300 K and 4495 $cm^2$/V.s at 77 K are reached in the AlGaN/GaN heterostructures. Both 2DEG mobility and density decrease dramatically when the AlGaN barrier is relaxed. The critical thickness of the AlGaN layer on GaN is determined between 65 nm and 75 nm, which is much higher than that predicted based on the theoretical calculation. It is attributed to the interaction of the misfit dislocations at the AlGaN/GaN interface. The favourable $Al_{0.15}Ga_{0.85}N$/GaN heterostructures for high 2DEG mobility is that the AlGaN spacer is between 10 nm and 20 nm in thickness and the whole AlGaN barrier is thinner than 60 nm.

**W11.15**
NEW MATERIALS THEORY BASED MODEL FOR OUTPUT CHARACTERISTICS OF AlGaN/GaN HETEROSTRUCTURE FIELD-EFFECT TRANSISTORS. J.D. Albrecht, P.P Ruden, University of Minnesota, Department of Electrical and Computer Engineering, Minneapolis, MN; S.C. Binari, K. Ikossi-Anastasiou, M.G. Ancona, Naval Research Laboratory, Electronics Science and Technology Division, Washington, DC.

A new, self-consistent model for the output characteristics of AlGaN/GaN heterostructure field effect transistors (HFETs) operated under high power conditions is presented. The model is built on results of Monte Carlo simulations of the relevant electron transport charcteristics and their temperature dependence. Temperature effects due to incomplete thermal dissipation in the devices are incorporated self-consistently. Furthermore, the model fully takes into account the ungated access channels between source and gate and between gate and drain. These access channels, which in conventional models are represented as linear parasitic resistances, are shown to have strongly non-linear current vs. voltage relationships that directly impact the observable HFET output currents. The model is applied to typical

transistor structures with varying lengths of source to gate and gate to drain access channels. The calculated output charcteristics are found to be in excellent agreement with experimental data for AlGaN/GaN HFETs with 1 micron gate length on sapphire substrates. Specific attention is given to the onset of current saturation. A detailed examination of the calculated channel potential and channel carrier concentration points to a complex interplay of velocity saturation, diffusion, and thermal effects as the ultimate origin of current saturation in these devices. The relative importance of the individual saturation effects is controled by the gate and drain voltages, the lengths of the access channels, and by the effectiveness of heat removal.

**W11.16**
HIGH-GAIN, HIGH-SPEED ZnO MSM ULTRAVIOLET PHOTODETECTORS. H. Shen and M. Wraback, US Army Research Laboratory, Sensors and Electron Devices Directorate, MD; S. Liang, Y. Liu, and Y. Lu, Rutgers University, Department of Electrical and Computer, NJ.

ZnO is a promising material for UV photodetector applications because of its wide bandgap and large photoresponse. However, ZnO photodetectors usually exhibit either a large photoresponse with a slow speed or a high speed with a small photoresponse. In this paper we report ZnO MSM detectors grown on R-plane sapphire, which exhibit both high photoresponse and high speed. The high-quality ZnO films were epitaxially grown on R-plane sapphire substrates by metalorganic chemical vapor deposition (MOCVD). In-situ nitrogen compensation doping was performed using NH3. The metal-semiconductor-metal ultraviolet sensitive photoconductors were fabricated on the epitaxial ZnO films. Al was used as the contact metal because of its low electron-affinity. The photoresponse of the detector was measured with a lamp and momochromator combination. A sharp spectral cutoff wavelength (20 dB across 15 nm) at 373 nm was observed. The photoresponsivity of this device exhibits a linear dependence upon bias voltage up to 10 V with a photoresponsivity of 400 A/W at 5 V. The speed of the device is measured with a 100 fs, 300-375 nm light pulse from a Ti:sapphire regenerative amplifier-pumped optical parametric amplifier. The measured rise and fall times are 1 and 1.5 ms, respectively, with a gain of 10. The photoresponse of ZnO consists of two parts: a rapid solid-state process (usually with a small response) and a slow process related to $O_2$ adsorption (with a large response). This slow photoresponse is significantly enhanced on the polycrystalline films due to the oxygen adsorption at the ZnO surface and grain boundaries. However, the solid- state-related fast process is enhanced in our sample by the improvement of crystalline-quality that reduces the defect-induced recombination. Simultaneously, the $O_2$ adsorption-related process is suppressed by reducing the electron carrier concentration through nitrogen compensation doping, as well as by essentially eliminating the grain boundaries in the single crystalline epitaxial ZnO films.

**W11.17**
AlGaN/GaN DISTRIBUTED BRAGG REFLECTOR ON SAPPHIRE GROWN BY MOCVD. Takashi Egawa, Naoyuki Nakada*, Hiroyasu Ishikawa, Takashi Jimbo and Masayoshi Umeno, Research Center for Micro-Structure Devices, Nagoya Institute of Technology, Gokiso-Cho, Showa-ku, Nagoya, JAPAN. *Department of Electrical and Computer Engineering, Nagoya Institute of Technology, Gokiso-cho, Showa-ku, Nagoya, JAPAN.

GaN-based vertical-cavity surface-emitting lasers (VCSELs) have attracted a great interest for various optical applications. In particular, the fabrication of distributed Bragg reflector (DBR) is a key technology for the successful VCSELs. In this study, we report $Al_{0.27}Ga_{0.73}N$/GaN DBR on a sapphire substrate with (0001) orientation (c face) grown by MOCVD.
The structure consisted a 30-nm-thick GaN buffer layer at 500°C, 1.5-$\mu$m thick GaN layer at 1080°C, 100 periods of $Al_{0.27}Ga_{0.73}N$/GaN strained layer superlattices (SLSs) and 30 pairs of quarter wave $Al_{0.27}Ga_{0.73}N$/GaN DBR. For comparison, the DBR structure without SLSs has been also grown on sapphire. The DBR without SLSs showed the cracks, the rough surface morphology and the reflectivity of 94%. On the other hand, the DBR with SLSs exhibited the peak reflectivity as high as 96% at the wavelength of 410 nm, which results from the improvement of the surface morphology and the suppression of the cracks. The abrupt heterointerfaces between the GaN and the $Al_{0.27}Ga_{0.73}N$ layers in the DBR with the SLSs was confirmed by the Auger electron spectroscopy measurement.
The reflectivity as high as 96% has been achieved for the $Al_{0.27}Ga_{0.73}N$/GaN DBR by use of $Al_{0.27}Ga_{0.73}N$/GaN SLSs, which is promising for the GaN-based VCSELs on sapphire.

**W11.18**
TEMPERATURE DISTRIBUTION IN InGaN-MQW LEDS UNDER OPERATION. Veit Schwegler, Christoph Kirchner, Matthias Seyboth, Markus Kamp, University of Ulm, Dept. of Optoelectronics, GERMANY; Wolfgang Limmer, Ulrich Stempfle, Rolf Sauer, University of Ulm, Dept. of Semiconductor Physics, GERMANY.

Heat generated by ohmic losses is a critical parameter for performance and lifetime of light-emitting diodes (LEDs). Due to the high bandgap voltages GaN-based devices are subject of severe ohmic heating. Increasing temperatures reduce the quantum efficiency and enhance diffusion of impurities (e.g. dopants, contact metals) as well as migration of dislocations. UV-emitting InGaN-MQW LEDs, grown by low pressure MOVPE on sapphire substrates, are investigated regarding their junction temperature at different injection currents. Consistent temperature distributions are determined by E2-LO phonon scattering (Raman), finite element simulations, and spatially resolved electroluminescence (EL). The region of increased temperatures is mainly restricted to the active area beneath the p-contact, whereas beyond the n-contact thermal equilibrium is established very soon. Even at moderate currents of 30 mA (corresponding to a power density of 705 $Wcm^{-2}$) temperatures as high as 140°C are determined for diced LEDs. The increasing temperatures obviously affect the EL wavelengths and intensities. The thermally induced red shift with increasing currents and the corresponding blue shift due to band filling are separated by nanosecond pulse injection and operation on a temperature controlled heat sink, respectively. For the present UV-LEDs with low In-contents the current (temperature) induced red shift (7 nm/80°C) clearly dominates as compared to the blue shift (1-2 nm at some hundred mA). The EL intensity shows an exponential decay between 5°C and 70°C, causing a 50% loss in brightness.

**W11.19**
PHOTOPUMPED VERTICAL CAVITY SURFACE EMITTING InGa/GaN/AlGaN LASERS OPERATING UP TO ROOM TEMPERATURE. W.V. Lundin, I.L. Krestnikov, A.V. Sakharov, A.S. Usikov, Zh.I. Alferov, A.F. Ioffe Physical-Technical Institute of Russian Academy of Sciences, St. Petersburg, RUSSIA; N.N. Ledentsov, J. Holst, A. Hoffmann, D. Bimberg, Technical University of Berlin, Berlin, GERMANY.

Photopumped surface-mode lasing at 400-415 nm is achieved in InGa/GaN/AlGaN heterostructures grown on sapphire substrate using metal-organic vapor phase epitaxy. Structures were grown at ambient pressures in the range of 200-600 mbar using hydrogen and argon as carrier gases for GaN and InGaN, respectively. Low-temperature-deposited AlGaN was used as a nucleation layer. The key point to achieve surface lasing in structures with significant external losses is to have an ultrahigh material gain in the active medium, while keeping its total volume small [1]. We used 12-fold stacked InGaN regions grown using rapid substrate-temperature-cycling technique either on top of a GaN buffer layer [2] or on top of a strain-compensated AlGaN/GaN Bragg mirror [3]. For the structures, where Fabry-Perot cavity was formed just by the GaN/sapphire and the GaN/air interfaces the threshold excitation density ($\sim$220 KW/cm$^2$) is weakly affected by the temperature of observation up to 110K, while it increases at 200K to 1 MW/cm$^2$. Applying a bottom distributed Bragg reflector (DBR) with maximum reflectivity exceeding 90% results in lasing up to room temperature at excitation density of 400 KW/cm$^2$. The lasing is confirmed by narrowing of the PL emission, threshold-like increase in the slope efficiency and by far-field pattern of the lasing emission, which is much narrower than that of the spontaneous surface emission of the cavity. In the DBR structures lasing emission develops on the longwavelength side of the PL spectra. Thus, the lasing clearly occurs via the localized states caused by In-rich nanodomains manifested in TEM and in optical stuidies. As opposite, the structures grown without bottom DBRs show lasing on the high-energy side of the PL emission spectrum. [1] I.L. Krestnikov et al. Phys. Rev. B. 59, July 1999. [2] A.V. Sakharov et al, Appl. Phys. Lett. 74, 28 June 1999. [3] I.L. Krestnikov et al, Appl. Phys. Lett., in print.

**W11.20**
INFLUENCE OF BARRIER DOPING ON THE OPTICAL PROPERTIES OF NITRIDE LIGHT EMITTERS. C. Sone, O.H. Nam, H.S. Park, E.S. Oh, B.J. Kim, J. Cho, S. Cho, J.W. Lee, S.H. Chae, I.H. Kim, Y.J. Park, and T.I. Kim, Samsung Advanced Institute of Technology, KOREA.

InGaN/InGaN multiple quantum well (MQW) structures are widely used materials for nitride light emitters. For acquiring high efficiency light emitters, optimization of the MQW structures is essential. Especially optical properties of the InGaN/InGaN MQW structures should be compared in optical and current injection cases. It is well known that Si doping on barrier is effective in increasing radiation efficiency of the MQW's and decreasing the threshold current density of laser diode. However, there are no detailed experimental results on the effects Si doping on the device performance of the light emitters. Firstly we have made InGaN/InGaN MQW structures for photoluminescence measurements. We have varied Si doping level

from 1E18 to 1E19 $cm^{-3}$ with different quantum well thickness (3-5 nm) in MQW's. Low power (~10 $W/cm^2$) photoluminescence properties are greatly affected by piezoelectric effects. Therefore the peak energy position and the peak intensity increases with Si doping level. Next, we grow violet laser diode structures with different Si doping level. With increasing Si doping level, the light output at 20 mA current level increases. We will report the detailed results of the lasing characteristics with varying Si doping level.

**W11.21**
ELECTRON BEAM PUMPING IN NITRIDE VERTICAL CAVITIES WITH GaN/$Al_{0.25}Ga_{0.75}N$ BRAGG REFLECTORS. Fritz Fedler, H. Klausing, J. Aderhold, D. Mistele, J. Stemmer, O. Semtchinova, J. Graul, Laboratory for Information Technology, Univ. of Hanover, Hannover, GERMANY; J. Dänhardt, S. Panzer, Fraunhofer Institute for Electron Beam and Plasma Technology, Dresden, GERMANY.

Electron beam pumped surface emitting lasers are of great interest concerning a variety of applications such as a high power light source and an ultraviolet light source for photolithography. Scanning E-Beam pumping experiments were performed at 40 keV excitation electron energy and 80 K to characterize the influence of GaN/$Al_{0.25}Ga_{0.75}N$ distributed Bragg reflectors (DBR) on the resonator properties by observing the surface emission spectra of the vertical cavity structures. The sample structures were grown by plasma-assisted molecular beam epitaxy (PAMBE) using a CARS25 from Oxford Applied Research. The active region of the two samples consisted of a 1.2 $\mu$m thick Si doped GaN layer and accordingly of a 1.2 $\mu$m thick 8.5-period multihetero (MH) structure based on GaN/$Al_{0.08}Ga_{0.92}N$, which was embedded in a vertical cavity formed by 15.5-period GaN/$Al_{0.25}Ga_{0.75}N$ Bragg reflectors. The total reflectivity of the upper DBR stack was increased by vapor deposition of a 100 nm thick Al layer. A separately grown DBR stack was firstly studied by optical transmission, reflection and Raman spectroscopy and experimental reflectance results were verified by simulations using the transfer matrix method. The surface emission spectra were measured for various e-beam currents and showed that luminescence emission maxima were located around 3.45 eV at 80 K for the sample with the MH structure as active region. Above an excitation power density of 0.85 $MW/cm^2$ optical modes appeared. With increasing excitation power density the number of modes increased and a broadening and redshift of the luminescence spectrum was observed. The influence of the primary beam electrons on the surface layer and on the optical parameters of the nitride vertical cavity will be discussed and a watch out for further studies on e-beam pumped vertical cavity laser structures will be given.

**W11.22**
MECHANISM OF EFFICIENT ULTRAVIOLET LASING IN A GaN/AlGaN SEPARATE CONFINEMENT HETEROSTRUCTURE. Sergiy Bidnyk, J.B. Lam, B.D. Little, G.H. Gainer, Y.H. Kwon, and J.J. Song, Center for Laser and Photonics Research and Dept of Physics, Oklahoma State University, Stillwater, OK.

We report on an experimental study of gain mechanisms leading to efficient lasing in an optically pumped GaN/AlGaN separate confinement heterostructure (SCH). The lasing threshold was measured to be as low as 15 $kW/cm^2$ at 10 K and 105 $kW/cm^2$ at room temperature. Strongly polarized (TE:TM > 300:1) lasing peaks were observed in a wavelength range of 358-367 nm. We found that high finesse lasing modes originated from self-formed microcavities due to cracks in the AlGaN and GaN layers. The "mode hopping" effect was observed with variations of temperature and/or excitation power. The energy positions of lasing modes of a single microcavity as well as the band-edge related emission from the GaN active layer and AlGaN cladding layers were measured as a function of temperature and compared with those of GaN epilayers. An analysis of the relative shift between the spontaneous emission and lasing peaks, combined with the temperature dependence of the lasing threshold, reveals that exciton-exciton scattering is the dominant gain mechanism leading to low-threshold ultra-violet lasing in the GaN/AlGaN SCH over the entire temperature range studied. Based on these results, we discuss possibilities for the development of ultra-violet laser diodes with a GaN active medium.

**W11.23**
VISIBLE EMISSION FROM GaN/AlN QUANTUM DOTS GROWN ON SILICON (111) SUBSTRATE. Benjamin Damilano, Nicolas Grandjean, Fabrice Semond, Jean Massies, Mathieu Leroux, Centre National de la Recherche Scientifique, CRHEA, Rue B. Grégory, Sophia Antipolis, Valbonne, FRANCE.

GaN quantum dots (QDs) in AlN matrix were grown on Si(111) substrate by molecular-beam epitaxy using ammonia as nitrogen precursor. The growth mode and relaxation process of GaN deposited at 800°C on AlN relaxed template were investigated in situ by reflection high-energy electron diffraction. We observed that the growth mode is two-dimensional (2D) even after the onset of plastic relaxation which occurs at 12 monolayers (ML, 1 ML=2.59Å). On the other hand, when a growth interruption is performed at GaN thicknesses greater than 3 MLs, three-dimensional (3D) islands instantaneously appear. GaN/AlN QD heterostructures on Si(111) substrate were then realized taking advantage of this 2D-3D transition. The structural properties of the dots were investigated by both atomic force microscopy and transmission electron microscopy. Intense room-temperature photoluminescence was observed from blue to orange depending on the dot size. This is obviously the consequence of the huge polarization field which takes place in nitride-based heterostructures.

**W11.24**
CHARACTERISTICS OF AN InGaN/GaN MULTIPLE QUANTUM WELL LIGHT EMITTING DIODES. G.C. Chi, J.K. Sheu, National Central University, Optical Science Center, Chung-Li, TAIWAN; M.J. Jou, Epistar Corporation, Hsinchu, TAIWAN.

An $In_{0.3}Ga_{0.7}N$/GaN multi-quantum well (MQW)LED, which consists of 9-period of InGaN/GaN MQW,were grown by metalorganic vapor phase epitaxy (MOVPE). The undoped MQW structure consists of 30A $In_{0.3}Ga_{0.7}N$ well layers and 70A GaN barrier layer. The p-type contact is Ni/Au(2nm/6nm) ultra thin transparent layers. The output power of a 350°-350 um size chip was around 1.5mW at 20 mA injection current, and forward voltage of 3.8 volts. The output power is sublinearly increased and the maximum output power around 3.5mW is obtained at 65mA injection current. The peak wavelength is around 465nm at 20mA. If there was strain free in the MQW, one may expect that the $In_{0.3}Ga_{0.7}N$ band edge emission peak at 450nm. A band gap narrowing effect is observed for this MQW LED. In addition, the emission spectra exhibit a blue-shift when injection current is increased. The shifts are about 140meV as the injection current increasing from 1mA to 500mA(pulse). These band gap narrowing and blue shift of electroluminescence may be understood as results of competition between a spectra redshifting mechanism of piezoelectricity-induced quantum-confined Stark effect and a blueshifting mechanism of band-filling and charge screening effects.

**W11.25**
DEPENDENCE OF AGING ON THE INHOMOGENEITIES IN InGaN/AlGaN/GaN LIGHT-EMITTING DIODES. V.E. Kudryashov, S.S. Mamakin, A.N. Turkin, A.E. Yunovich, M.V. Lomonosov Moscow State University, Department of Physics; A.N. Kovalev, F.I. Manyakhin, Moscow Institute of Steel and Alloys.

In a recent paper we have shown that minor differences in quantum efficiency (of 10% at working currents) of green LEDs based on $In_xGa_{1-x}N/Al_yGa_{1-y}$/GaN heterostructures with quantum wells are connected with large differences of intensity and quantum efficiency dependence on current [1]. These differences are caused by different distribution of effective charges in the space charge regions and role of tunnel component of currents. In this work we study a correlation between mechanisms of aging in these diodes and the nonuniformities in the heterostructures due to this different distribution. The procedure of aging at the forward current J= 80 mA was the same as in [2]. [1] V.E. Kudryashov, S.S. Mamakin, A.N. Turkin, A.E. Yunovich, A.N. Kovalev*, F.I. Manyakhin*. ICNS-3, Montpellier, July 1999, Abstr. N. [2] A.N. Kovalev, F.I. Manyakhin, A.E. Yunovich. MRS Int. J. of Nitride Semic. Res., 1998, 3/52. http:\\nsr.mij.mrs.org\3\52.

**W11.26**
OPTICAL SPECTROSCOPY AND COMPOSITION OF InGaN. K.P. O'Donnell, R.W. Martin, M. E. White, Department of Physics and Applied Physics, University of Strathclyde, Glasgow, SCOTLAND; Koen Jacobs, W. Van der Stricht, P. Demeester, Department of Information Technology, University of Gent, Gent, BELGIUM; A. Vantomme, M.F. Wu, KULeuven, Leuven, BELIUM; J.F. Mosselmans, CLRC, Daresbury Labs, ENGLAND.

The extension of nitride technology to the full visible spectrum is a technical challenge that depends upon the successful incorporation of increasing levels of indium nitride into gallium nitride, while maintaining the high fluorescence efficiency of the resulting solid solution. At present, commercial light emitting devices based upon indium gallium nitride enjoy unmatched performance in the violet (~400 nm), blue (~450 nm) and green (~520 nm) spectral regions. Nichia Company have also produced amber InGaN LEDs, which peak near 590 nm. Recently, we reported emission peaks up to 650 nm in epilayers grown at low temperatures [O'Donnell et al, APL 73, 3273 (1998)]. On the basis of our description of the Stokes' shift in InGaN epilayers [Martin et al, APL 74, 263 (1999)] we now predict a limiting value, for InGaN intrinsic emission, of 980 nm peak. Although this predicted value is 0.6 eV lower in energy than the band gap of pure indium nitride, we confirm its validity by spectroscopic measurements of layers with peak emission wavelengths up to 950 nm. As remarkable

as this result is, we have further directly measured the indium content of a wide range of light-emitting InGaN layers. Different measurement techniques, Rutherford Backscattering Spectrometry, Extended X-ray Absorption Fine Structure and Energy Dispersive X-ray Fluorescence analysis, show remarkably good agreement. Violet-emitting layers contain 8% In, blue layers 14% and green layers 21%. These values are generally lower than those estimated using X-ray diffraction techniques by a factor of about 2. Layers that emit light with a peak near 700 nm contain no more than 40% In. Extrapolating to the limit set by the Stokes' shift prediction mentioned above yields a limiting indium concentration of only 50%. The profound consequences of these results on future technical innovations and current theoretical models of InGaN will be discussed.

**W11.27**
CARRIER DYNAMICS OF PIEZOELECTRIC GaN/InGaN QUANTUM WELLS. A.N. Cartwright, Paul M. Sweeney, Thomas Prunty, Menq J. Pan, Electrical Engineering, State University of New York at Buffalo, NY; David P. Bour, Michael Kneissl, Electronic Materials Laboratory, Xerox-Palo Alto Research Center.

A self-consistent theoretical model, and experimental time-integrated and time-resolved photoluminescence measurements of piezoelectric fields in GaN/InGaN quantum wells is presented. Specifically, multiple quantum wells (MQW) embedded within the intrinsic region of GaN/$In_{(x)}Ga_{(1-x)}N$ ($x$=0.2 and 0.3) p-i-n structures grown by MOCVD on <0001>-oriented sapphire substrates were studied. Theoretically, we calculated the built-in fields (in-well and barrier fields) in these p-i(MQW)-n structures including the piezoelectric field. Moreover, we performed calculations of the electron and hole wave-functions within the quantum wells using a variational technique, as a function of in-well electric field, and estimated the quantum-confined Stark effect (QCSE). Experimentally, we performed time-integrated and time-resolved photoluminescence measurements of p-i(MQW)-n samples with two, ten and twenty quantum wells, pumped by the frequency doubled output of a femtosecond Ti: Sapphire laser, as a function of excitation power and wavelength, and sample temperature. The magnitude of the yellow emission in the time-integrated spectra served as an indicator of the magnitude of the built-in p-i-n electric field and elongation of carrier recombination lifetimes. Furthermore, the time resolved photoluminescence measurements of these samples showed a blue-shift of the photoluminescence consistent with theoretical calculations that include the piezoelectric field. More importantly, the observed energy shift was proportional to the calculated in-well fields, consistent with our calculated QCSE for these structures. Moreover, carrier lifetimes were 500-700 ps for the high-energy (shifted) emission but the low energy emission exhibited long decay times of 4-5 ns at 15K. Again, these results are consistent with our model of the recombination of carriers that are spatially separated by an electric field.

**W11.28**
SIGN OF THE PIEZOELECTRIC FIELD IN ASYMMETRIC GaInN/AlGaN/GaN SINGLE AND DOUBLE QUANTUM WELLS ON SAPPHIRE AND SiC. Jin Seo Im, A. Hangleiter, Technische Universitaet Braunschweig, Institut fuer Technische Physik, Braunschweig, GERMANY; J. Off, F. Scholz, Universitaet Stuttgart, 4. Physikalisches Institut, Stuttgart, GERMANY.

The piezoelectric field effect in GaN-based quantum wells, which has been recently lively discussed, provides in-depth explanation of their optical properties. To explore the effect in more detail, we have designed GaN/AlGaN asymmetric double quantum well (ADQW) structure, which consists of a 2 nm and a 4 nm GaN QW separated by a 2.5 nm AlGaN layer. In the presence of the piezoelectric field, we expect different behavior if the position of the two QW's is exchanged with respect to the growth direction. Furthermore, the ADQW enables us to monitor inter- and intra-well transitions separately, which are sensitive to the internal piezoelectric field. Indeed, we have observed an inter- and two intra-well transitions in the photoluminescence under resonant excitation, and their lifetimes and emission energies confirm that these transitions are strongly influenced by the field. The asymmetry of those ADQW's is compared to the asymmetry in asymmetric barrier structures, i.e. a GaInN QW sandwiched by an AlGaN and a GaN layer. The oscillator strength depends on the position of the barrier layer to the growth direction, which allows us to determine the sign of the field. Using this sample structure grown on sapphire and SiC substrate, we found that the sign of the field is the same in both cases. This result leads us to the conclusion that crystallographic polarity is not changed by using sapphire or SiC substrates.

**W11.29**
RELAXATION AND RECOMBINATION DYNAMICS IN InGaN/GaN MULTIPLE QUANTUM WELLS: THERMALIZATION AND CARRIER FREEZE OUT IN LOCAL POTENTIAL FLUCTUATIONS. J. Christen, T. Riemann, P. Fischer, Inst of Exp Physics, Univ Magdeburg, GERMANY; J. Holst, A. Hoffmann, Inst of Solid State Physics, TU Berlin, GERMANY; M. Heuken, AIXTRON AG, Aachen, GERMANY.

The carrier dynamics in a 10x InGaN/GaN MQW ([In] = 0.125, $L_Z$ = 4.0 nm, $L_B$ = 7.7 nm) MOCVD grown on GaN/c-sapphire substrate is comprehensively characterized applying spatially and time resolved cathodoluminescence (CL), photoluminescence (PL) as well as gain spectroscopy. The excitation density is varied from 1.3 $\mu W/cm^2$ up to 66 $kW/cm^2$. The InGaN MQW exhibits a very intense blue emission centered around 2.8 eV (FWHM = 50 meV, i.e. $\sigma$ = 21 meV) shifting with increasing cw CL excitation power according to E = $E_0$+25meV•log($P/P_0$) which is consistent with filling of localized states within the statistical [In]-distribution. From CL wavelength images mapping the local emission energy we find an almost Gaussian distribution yielding $E_0$ = 2.841 eV and a standard deviation of $\sigma$ = 7 meV ($\sigma_{In}$ = 0.005). Time resolved CL measurements yield a spectrally dependent carrier lifetime increasing from 8.8 ns up to 120 ns with decreasing photon energy. The InGaN emission line shows a monotonous redshift of $\Delta E$ = 60 meV during 4.5 $\mu$s decay (E = $E_0$-25meV•log($t/t_0$)) directly visualizing the carrier thermalization into In-rich low-energy states. While the GaN luminescence follows Varshni's temperature dependence a strong S-shape behavior is observed for the InGaN related emission. Starting at 4.5 K for a PL excitation density of 0.13 $W/cm^2$ an initial redshift of 25 meV is compensated by a blueshift of 36 meV up to 170 K, leading to a minimum of the emission energy at 70 K. For higher PL excitation densities this minimum becomes less pronounced and vanishes almost completely at a CL excitation density of 2.7 $kW/cm^2$. From an Arrhenius plot of the PL intensity we determine thermal activation energies of 22 meV and 8 meV for thermionic emission of the freezed out carriers. From the intensity dependent gain measurements the influence of In-fluctuations on the optical amplification was investigated and be discussed in detail.

**W11.30**
DEFECTS, PHASE SEPARATION AND COMPOSITION FLUCTUATION IN InGaN LAYERS GROWN BY MOCVD. Pierre Ruterana, Laboratoire d'Etudes et de Recherches sur les Matriaux, UPRESA CNRS 6004, IMSRA, Caen, FRANCE. Marie-Antoinette Poisson, Thomson-CSF, Laboratoire Central de Recherches, Domaine de Corbeville, Orsay, FRANCE; Franck Omnes and David Schenck, CRHEA-CNRS, Sophia Antipolis, Valbonne, FRANCE.

Electron microscopy analysis has been carried out on ternary layers and quantum wells grown on top of at least 200 nm GaN films. Our attention was focussed on InGaN layers whose Indium compositions was varied from 2 to 20 %. Samples from two growth facilities were investigated. In both cases the samples were either made of a 100-200 nm ternary layer, or a series of QWs. In one series, fairly strong emission was obtained in photoluminescence. For the thick InGaN layer whose nominal composition was 17 %; EDS measured composition is closed to 12-13 %. Close examination of the layer surface shows that when threading dislocations emerge, nanometric precipitate have formed. EDS analysis shows that these precipitate correspond to InN. In the second series of samples, as soon as the In concentration was increased above 10 % V shape defects form which cross the whole ternary layer. These defects are clearly connected to c and a+c threading dislocations. In many cases more than one dislocation hit the surface in the middle of such defects. Their connection to the growth process and indium concentration will be discussed. In the quantum well sample, it is noticed that the QW average thickness is uniform, however, the contrast change indicates that the strain distribution is not constant which probably means that the indium composition fluctuates in nanometric areas.

**W11.31**
STUDY OF PHASE-SEPARATED THIN LAYERS OF InGaN GROWN BY METALORGANIC-VAPOR-PHASE-EPITAXY. P. Li, S.J. Chua, Center for Opto-electronics, Dept. of Electrical Engineering, National University of Singapore, SINGAPORE; W. Wang, H.M. Hao, Institute Of Material Research and Engineering, SINGAPORE; T. Sugahara, S. Sakai, Satellite Venture Business Laboratory, Department of Electrical Engineering, University of Tokushima, Minami-Josanjima, Tokushima, JAPAN.

Four phase separated $In_xGa_{1-x}N$ thin films were grown by low-pressure metalorganic-vapor-phase-epitaxy (MOVPE) on sapphire substrates and characterized by photoluminescence (PL) with variable excitation intensity and temperature and Time-resolved PL(TRPL). The effects of dislocations on the growth and emission process was investigated by Atomic Force Mocroscopy (AFM) and Cathodoluminescence (CL) mapping. All the four samples show dominant peaks at around 2.9eV and peaks or shoulders at 2.8eV at 6K. One sample, with a 19.53% In-content determined by HRXRD, has the strongest peak at 2.8eV compared with other samples. The

temperature-dependent PL showed that the low energy peak exhibits a complicated (red-shift, blue-shift, red-shift, blue-shift, and red-shift) temperature dependence from 6K to 300K. The high energy peak exhibits a red-shift as the temperature is increased from 6K and quenches at about 150K. The low energy peak dominates at 300K. The results of the excitation power-dependent PL and the TRPL exclude the possibility that the low energy peak comes from DAP. We conclude that the low energy peak is due to the localized near-band edge transition from the phase-separated InGaN mesoscopic structure with high In-content. The strong luminescence of the low energy peak may be due to the quantum confinement enhancement in the form of nanostructures or quantum dots. We come to a picture for the phase-separated InGaN in which the In-rich regions have the form of quantum dots with different sizes which were imbedded in the rather uniform low-In content environments. The four samples exhibit different morphologies but they all have different degree of spiral growth mode. The sample with the strongest low energy peak (the largest degree of phase separation) has the highest density of both large (diameter 700nm) and small (diameter 100nm) 'hexagonal pits' which are inverted hexagonal pyramids formed at the ends of TDs. The sides of the 'pits' are $(10\bar{1}1)$ surface. Thus, the strong preference for In surface segregation and occupation of $(10\bar{1}1)$ surface which was first put forwarded by Northrup using the first-principle calculation was demonstrated. CL mapping is being done in Prof. S. Sakai's group in the Univ. of Tokushima, preliminary results showed that the longer wavelength emission did come from the region near the 'hexagonal' pits which demonstrated that phase-separation is prominent near the V-defects.

**W11.32**

EMISSION ENHANCEMENT OF GaN/AlGaN SINGLE-QUANTUM-WELLS DUE TO SCREENING OF PIEZOELECTRIC FIELD. A. Kinoshita[1,2], H. Hirayama[1], P. Riblet[1], M. Ainoya[1,2], A. Hirata[2], Y. Aoyagi[1]; [1] The Institute of Physical and Chemical Research (RIKEN), Saitama, JAPAN; [2] Dept of Chemical Engineering, Waseda Univ., Tokyo, JAPAN.

The screening of piezoelectric field in the QW plays a significant role for the increase of transition probability. In this report, the effect of Si-doping on optical properties was systematically studied in $GaN/Al_{0.10}Ga_{0.90}N$ single quantum well (SQW). The SQW was grown on SiC (0001) surface by metalorganic vapor phase epitaxy (MOVPE). Structures consist of Si-doped or undoped GaN SQW with 500nm-thick $Al_{0.10}Ga_{0.90}N$ buffer and 25nm-thick $Al_{0.10}Ga_{0.90}N$ capping layer. Si doping concentration in the well was varied from 2 x $10^{18}$ to 7 x $10^{18}$ $cm^{-3}$ and their thickness was varied from 2nm to 5nm. Information on the optical property as functions of well thickness and/or Si-doping concentration were extracted from the photoluminescence (PL) spectrum measured under excited with He-Cd laser (325nm) as low excitation conditions or excimer laser (308nm) as high excitation conditions. PL intensity and PL peak blue shift shows an increase with increasing Si-doping concentration. The magnitude of these intensity enhancement and blue shift was found to drastically increase with increasing well thickness. The typical value of PL intensity enhancement ratio was 30 times for 5nm-thick SQW with Si doping concentration of 7 x $10^{18}$ $cm^{-3}$. In addition, PL peak energy as a function of well thickness was measured for undoped and highly Si-doped SQWs under high and low excitation conditions. For undoped SQW, a separation of PL peak energy between high and low excitation spectrum was observed, which was not observed for Si-doped SQW. These results indicates that the optical properties of GaN/AlGaN SQW was drastically improved due to the screening of piezoelectric field.

**W11.33**

COMPOSITION FLUCTUATIONS IN InGaN GROWN IN PRODUCTION TYPE MOVPE REACTORS. D. Gerthsen, B. Neubauer, E. Hahn, A. Rosenauer, Karlsruhe Univ(TH), Lab.f. Elektronenmikroskopie, GERMANY; H. Protzmann, M. Luenbuerger, M. Heuken, AIXTRON AG, Aachen, GERMANY; Michael Bremser, AIXTRON Inc., Dept.of Technology Transfer, CA.

InGaN/GaN heterostructures grown in AIXTRON single and multiwafer production reactors were studied by conventional transmission electron microscopy to assess the morphology of the epilayers and the type and density of crystal defects. High-resolution transmission electron microscopy was applied for the investigation of the structure on an atomic scale. The heterostructures were grown by metal organic vapour deposition using the standard precursors on $Al_2O_3(0001)$ substrates. Two series of samples were investigated where only one parameter was varied. In the first series, the InGaN growth temperature was changed while the duration of the InGaN deposition was varied in the second series. An image evaluation procedure based on high-resolution lattice fringe images was applied to investigate the composition of the InGaN layers. The procedure involves the measurement of the (0002) plane distances in InGaN which are linearly correlated with the indium concentration. All InGaN layers with average In-concentrations of more than 6% show composition fluctuations on a scale of a few nanometers. The local maximum In-contents deviate up to a factor 3 from the mean In-content. The average In-concentration can be strongly influenced by the variation of the growth temperature. Higher In-contents are incorporated by lowering the growth temperature from 860°C to 800°C which also induces a shift of the emitted wavelength measured by room-temperature photoluminescence spectroscopy from 390 nm to 480 nm. Results obtained from the series with different deposition times indicate that the average In-contents differ. For a growth duration of 1 min the average In-concentration amounts to 6%. 16% is observed for a 10 min growth duration with a pronounced accumulation of the indium in the upper part of the layer. Despite these composition fluctuations on the nm scale wavelength uniformities of less than 1 nm across a full two inch wafer measured routinely.

**W11.34**

CORRELATION BETWEEN STRUCTURAL PROPERTIES AND OPTICAL AMPLFICATION IN InGaN/GaN HETERO-STRUCTURES GROWN BY MOLECULAR BEAM EPITAXY. A. Kaschner, J. Holst, U. von Gfug and A. Hoffmann, Institut für Festkörperphysik, TU Berlin, Berlin, GERMANY; F. Bertram, T. Riemann, D. Rudloff, P. Fischer and J. Christen, Institut für Experimentelle Physik, Otto-von-Guericke-Universität, Magdeburg, GERMANY; R. Averbeck and H. Riechert Infineon Technologies, Corporate Research, München, GERMANY.

Heterostructures of compound group-III nitride-semiconductors are of great importance for the rapidly increasing market of optoelectronical devices in the blue spectral range [1]. While most articles in this field report about investigation of samples grown by vapor phase epitaxy such as MOCVD and MOVPE we focus here on InGaN grown by molecular beam epitaxy (MBE). This may give some new physical insight since growth conditions are not at thermodynamic equilibrium and therefore one expects different properties, e.g. considering effects like phase separation and fluctuations of the indium content [2]. We comprehensively studied InGaN/GaN heterostructures and multiple quantum wells with a variety of methods in optical spectroscopy. Micro-photoluminescence and cathodoluminescence (CL) results show the variation in emission wavelength at different scales and this reflects the degree of compositional fluctuations in the samples. We yield information of the decay times of the main emission lines using time-resolved photoluminescence spectroscopy. The temporal behavior exhibits a multiple exponential decay on a large time scale which is typical for the InGaN material system at high excitation energies [3]. Furthermore we performed gain measurements in edge-stripe geometry at 4 K and room temperature. Lasing of a MQW with 4 nm well width was observed at 4 K. Gain values up to 60 $cm^{-1}$ at helium temperatures were found in samples with low indium fluctuations. From all these findings we draw conclusions concerning the influence of compositional fluctuations on the optical gain.

**W11.35**

OPTICAL PROPERTIES OF AlGaN QUANTUM WELL STRUCTURES. Hideki Hirayama[1], Yasushi Enomoto[1,2], Atsuhiro Kinoshita[1,2], Akira Hirata[2], and Yoshinobu Aoyagi[1]; [1]RIKEN(The Institute of Physical and Chemical Research), [2]Waseda Univ.

AlGaN alloy is very attractive material for the application to ultra-violet (UV) laser diodes (LDs), light emitting diodes (LEDs) or photo-detectors, because of wide UV direct transition emission range between 3.4eV (GaN) and 6.2eV (AlN). In this work, as a trial for the strong UV light-emitting material, we fabricated $Al_xGa_{1-x}N/Al_yGa_{1-y}N$ (x=0.70-0.24, y=0.12) multi-quantum-well (MQW) structures using metal-organic chemical-vapor-deposition (MOCVD), and demonstrate intense UV photoluminescence (PL) emission of 260nm band from the MQW. Heterostructures consisting of 0.3 $\mu$m-thick $Al_{0.70}Ga_{0.30}N$ buffer layer, 5-layer MQW with several-nm-thick $Al_{0.12}Ga_{0.88}N$ quantum well and 6nm-thick $Al_{0.70}Ga_{0.30}N$ barrier was grown on 6H-SiC(0001) substrate. We obtained intense single-peak PL emission of 262nm from $Al_{0.70}Ga_{0.30}N/Al_{0.12}Ga_{0.88}N$ MQW with 3nm thick quantum well at 77K. The intensity of the AlGaN MQW at 77k was as strong as that of an $In_{0.2}Ga_{0.8}N/In_{0.02}Ga_{0.98}N$ single-QW. We systematically studied on optical properties of AlGaN MQWs as functions of quantum well thickness and Al content of the barrier layer. By changing the Al content of barrier and buffer layers from 0.24 to 0.70, we obtained the UV PL peak of MQWs ranging from 330nm to 260nm. Also we found that the optimized well thickness for the intense PL emission was around 3nm for various Al content of AlGaN barrier. In the conference, we will also demonstrate the temperature dependence of PL and photoluminescence excitation spectra (PLE) of the AlGaN MQWs.

**W11.36**
TEMPERATURE DEPENDENCE OF THE PHOTO-LUMINESCENCE OF MOLECULAR BEAM EPITAXY GROWN (Al,Ga)N/GaN QUANTUM WELLS. M. Leroux, N. Grandjean, B. Damilano, S. Dalmasso and J. Massies, CRHEA-CNRS, Rue B. Grègory, Sophia Antipolis, Valbonne, FRANCE.

(Al,Ga)N/GaN quantum wells have been grown by molecular beam epitaxy. The well width, barrier width and barrier Al content have been varied. These quantum wells were studied by reflectivity and photoluminescence. We discuss the temperature dependence (10K-300K) of luminescence intensities as a function of the well parameters. Such a study is first shown to allow a convenient measure of exciton localization energies. They range between 10 and 30 meV, depending on well width and Al composition. The determination of intrinsic excitonic energies is a key point for an unambiguous measurement of the heterostructural polarization fields. In narrow wells, where these polarization fields have no major role on radiative lifetimes, the quenching of the photoluminescence can be described by exciton escape. This is not the case for wider wells where the activation energy for quenching is significantly smaller than the escape energy. We discuss the possible reasons : single carrier escape or activation of non radiative centers. We have finally studied samples in which the negative effect of polarization fields on radiative lifetimes have been diminished, either by intentional Si doping or by the insertion of a polarization counter-balancing AlN layer in the well.

**W11.37**
CHARACTERIZATION OF InGaN QUANTUM WELLS GROWN BY MOLECULAR BEAM EPITAXY (MBE) USING AMMONIA AS THE NITOGEN SOURCE. F. Semendy, AMSRL-SE-EM, SEDD, Army Research Lab, Adelphi, MD; L.K. Li, M.J. Jurkovic, W.I. Wang, Electrical Engineering Dept, Columbia Univ, New York, NY.

InGaN, GaN and AlGaN were grown by molecular beam epitaxy (MBE) using ammonia as the nitrogen source. The samples were grown on (0001) sapphire substrates. Prior to growth, the sapphire substrate was cleaned by a SVT Associate RF nitrogen source at 800 C for 10 minutes. After the cleaning high purity ammonia was introduced through a gas injector for the growth of InGaN, GaN and AlGaN. A low substrate temperature (below 650 C) was used for InGaN to avoid the evaporation of In from the growing surface. RHEED was employed to monitor the crystal growth. The growth of GaN buffer layer required particular attention. For low temperatures (700 C), facet-like RHEED patterns were often observed. RHEED patterns for the layers grown above 750 C remained streaky throughout the entire growth. For InGaN, it was observed that lower substrate temperatures (below 650 C) were required to maintain two-dimensional growth mode and to retain In in the epitaxial layer. High growth temperatures resulted in complete evaporation of In and the resultant layer became pure GaN. Photoluminescence of the InGaN quantum wells showed band-edge emissions at 460 nm at low temperatures (10K). TEM studies indicated very good crystallographic quality of the GaN films with the commonly oberved reduction of the dislocation density with the increased distance away from GaN/sapphire interface. The InGaN layers are single crystalline and epitaxial, and revealing clean and uniformely strained interfaces with the GaN layers. Part of the threading dislocations initiated from the GaN/sapphire interface do not propagate through the InGaN layers. Detailed results will be reported.

**W11.38**
COMPARITIVE STUDY OF STRUCTURAL PROPERTIES AND PHOTOLUMINESCENCE IN InGaN LAYERS. A. Vantomme, M.F. Wu, S. Hogg, G. Langouche, Instituut voor Kern- en Stralingsfysica, Univ. of Leuven, BELGIUM; K. Jacobs, I. Moerman, Dept of Information Technology, Univ. of Gent-IMEC, BELGIUM; M.E. White, K.P. O'Donnell, Dept of Physics and Applied Physics, Univ. of Strathclyde, Glasgow, SCOTLAND, UNITED KINGDOM; L. Nistor, Institute of Atomic Physics, Bucharest, ROMANIA; J. Van Landuyt, EMAT, Univ. of Antwerp, BELGIUM; H. Bender, IMEC vzw, Leuven, BELGIUM.

Rutherford backscattering and channeling spectrometry (RBS), photoluminescence (PL) spectroscopy and transmission electron microscopy (TEM) have been used to investigate macroscopic and microscopic segregation of indium in InGaN layers. Two heteroepitaxial, highly strained $In_xGa_{1-x}N$ layers were grown by MOCVD at relatively low temperature on a GaN buffer layer on sapphire substrates. The exact In fraction (ranging from 0.2 to 0.4) was mapped at a large number of distinct points on these samples by RBS. A nitrogen excess was observed to correlate with higher In content. The corresponding crystalline quality deteriorates with increasing In fraction, and/or with increasing N excess. PL measurements revealed a direct, linear relationship between PL peak energy and In content. Taking into account the linear variation of the PL peak with bandgap (1), this result implies that band bowing is absent. Indium content measured by RBS is systematically lower than that expected from previous calibrations based on a comparison of PL with X-ray diffraction. An indium concentration of 40%, the highest measured in this work, corresponds to a PL peak of 650 nm, strongly suggesting that the light-emitting regions of the sample are very indium-rich compared to the average measured by RBS. Cross-sectional TEM shows distinctive layering of the InGaN layers, while plan view images show a high density of dislocations. The TEM study further reveals the presence of specific contrast features with sizes of order 10 nm. The question of the identification of these features with InN quantum dots, as a result of phase separation, is currently under investigation. (1) R.W. Martin et al, Appl. Phys. Lett. 74, 263 (1999)

**W11.39**
LATTICE MODES AND FREE-CARRIER RESPONSE OF $Al_xGa_{1-x}N$ AND $In_xGa_{1-x}N$ HETEROSTRUCTURES MEASURED BY INFRARED ELLIPSOMETRY. M. Schubert, T.E. Tiwald, J.A. Woollam, Univ Nebraska-Lincoln, Center for Microelectronic and Optical Materials Research, Dept of Electrical Engineering, Lincoln, NE; A. Kasic, Universitat Leipzig, Abt. Halbleiterphysik, Fakultat Physik und Geowissenschaften, Leipzig, GERMANY; J. Off, B. Kuhn, F. Scholz, Universitat Stuttgart, Stuttgart, GERMANY.

Control and understanding of free-carrier properties in group III-nitride heterostructures is necessary for optimization of electro-optical device performance. However, non-destructive measurement of free-carrier parameters in device heterostructures is a challenge. The dielectric functions for wavelength ranges where free-carrier and optical-phonon properties affect the optical response are mostly unknown for group III-nitride materials. We therefore investigate the long-wavelength dielectric response of $Al_xGa_{1-x}N$ and $In_xGa_{1-x}N$ heterostructures ($0<x<1$)) using infrared spectroscopic ellipsometry (IR-SE) for wavelength from 1 .. 35 $\mu$m. The samples were grown by metal-organic vapor-phase epitaxy on c-plane sapphire. The infrared-active phonon branches as well as their polar strength, i.e., their transverse-optical (TO) and longitudinal-optical (LO) splitting, influence the dielectric response of $Al_xGa_{1-x}N$ and $In_xGa_{1-x}N$. Likewise, the presence of free carriers within a heterostructure component affects the long-wavelength absorption behavior, and LO-phonon-plasmon coupling occurs. Analysis of the IR-SE data from the heterostructure components provides sensitivity to the anisotropic infrared dielectric functions of the wurtzite III-nitrides. Coupling of plasmons to LO-phonons in p- and n-type doped GaN reveals free-carrier properties, such as free-carrier concentration and anisotropic carrier mobility within the GaN films. We also observe fairly high concentrations of free carriers in unintentionally doped $Al_xGa_{1-x}N$ films. We obtain the composition dependence of the phonon energies of the ternary $A^{III}{}_xB^{III}{}_{1-x}N$ solid solutions, and we find a two-mode behavior in $Al_xGa_{1-x}N$, whereas a single-mode behavior is sufficient to explain the infrared response of $In_xGa_{1-x}N$.

**W11.40**
OPTICAL MEMORY USING BIPHOTONIC UPCONVERSION IN Er FIB IMPLANTED GALLIUM NITRIDE. R.C.J. Chi, B.K. Lee, L.C. Chao, J. Cheng, I. Chyr and A.J. Steckl, Nanoelectronics Laboratory, University of Cincinnati, Cincinnati, OH.

This paper discusses an optical memory device using up-conversion emission from rare-earth-doped gallium nitride. The basic mechanism involves a real state up-conversion process by two lasers at different frequency where the RE ions is excited through an intermediate energy level with a relatively long lifetime. Because of this long lifetime, the real state up-conversion process is much more efficient than conventional up-conversion which utilizes the absorption of two photons of the same energy through a virtual state which has a very short lifetime. This bi-photonic mechanism can be used to read back information stored in various locations in the optical memory host. This is accomplished by using two pump lasers which are co-linearly scanned at various memory locations. The information is stored in the optical memory by implanting a closely-spaced pattern of RE ions into a GaN medium. This could be accomplished by focused ion beam (FIB) implantation with a spacing as small as 10 to 50 nm (depending on species, energy, substrate). Theoretically, this could result in an area bit density of $10^{10}$ to $10^{12}$ /cm$^2$. The first implementation of this optical memory in GaN using 200 keV Er FIB implantation with a 1E15 /cm$^2$ dose is discussed. The necessary characterization system consisting of high precision (20nm) stage, CCD spectrometer, pump lasers is controlled by custom designed automation software based on the Labview$^{TM}$ system. Localized bi-photonic emission was obtained using pump lasers at 840 and 1000 nm, Photons of these two energy cause sequential transition from the ground state to the $^2H_{11/2}$ and $^4S_{3/2}$ states. Radiative transitions from the excited states to the ground level result in green emission at 523 and 546 nm. Preliminary memory arrays (3×3) have been fabricated to prove the feasibility of this concept.

**W11.41**
OPTICAL SPECTROSCOPY OF InGaN EPILAYERS IN THE LOW INDIUM COMPOSITION REGIME. M.H. Crawford, J. Han, M.A. Banas, G.A. Petersen, S.M. Myers and J.J. Figiel, Sandia National Laboratories, Albuquqerque, NM.

While a great deal of progress has been made in the development of InGaN-based light emitters, the role played by indium (In) in contributing to the optical efficiency is still quite controversial. Theories proposed to explain the high optical efficiencies of InGaN alloys include carrier localization at In rich regions (1) and the reduction of non-radiative recombination centers when In is included in the growth (2). Understanding the role of In is critical to the optimization of UV LEDs and laser diodes, where little or no In is typically used in the active layers. To gain insight into this important issue, we have grown a series of Si-doped InGaN epilayers, by MOVPE, with the In composition x varying from 0 to 0.10. Many of the samples are in the low composition regime ($x<0.04$) to investigate how the unusual optical properties of InGaN alloys develop. A determination of the In composition is obtained by both Rutherford backscattering spectrometry and x-ray diffraction. Room temperature photoluminescence (PL) data reveal a factor of 25 increase in the integrated PL intensity as the PL peak wavelength shifts from 364 nm - 397 nm with increased In incorporation. Temperature-dependent (10K-300K) PL results show that the thermal quenching of PL integrated intensity is reduced with increased In composition, and varied from a factor of 10 to a factor of 50 for the samples studied. Time resolved PL studies have been performed to study the recombination dynamics as a function of In composition and will be reported. (1) T. Mukai, et. al., J. Cryst. Growth 189/190 778 (1998), (2) Y. Narukawa, et. al., Appl. Phys. Lett., 74, 558 (1999). Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company for the U. S. Dept. of Energy under contract DE-AC04-94AL85000.

**W11.42**
ELECTRONIC RAMAN SCATTERING FROM Mg-DOPED WURTZITE GaN. K.T. Tsen, C. Koch, Y. Chen, Department of Physics and Astronomy, Arizona State Univ, Tempe, AZ ; H. Morkoc, Department of Electrical Engineering, Virginia Commonwealth Univ, Richmond, VA; H-X Jiang, Department of Physics, Kansas State Univ, Manhattan, KS.

Electronic Raman scattering from heavily Mg-doped wurtzite GaN has been observed by using Raman spectroscopy at T = 300 K. Both MBE-grown and MOCVD-grown samples yielded similar results. The incident photon excites the ground state of Mg impurities to the excited states and the energy difference between the scattered photon and the incident photon detected in our Raman spectra provides a unique signature of light scattering from Mg-impurities in GaN. From the analysis of the temperature dependence of the electronic Raman signal from Mg-doped wurtzite GaN, we obtain the ionization energy of the Mg impurities in GaN to be 170 ± 5 meV.

**W11.43**
PROPERTIES OF A BLUE EMISSION BAND OF BULK INGAN. Hisashi Kanie, Takahiro Kawano, Science Univ Tokyo, Dept of Applied Electronics, Chiba, JAPAN.

Recent advance in growth technique allows InGaN based violet laser diodes to have a lifetime longer than 10000 hr. The emission mechanism of InGaN active layers, however, is not yet well understood. As we have succeeded in synthesizing InGaN bulk crystals by the nitridation of Ga and In compound mixtures, we can investigate optical properties of InGaN without a nuisance of growth induced stresses. The grown InGaN crystals have a diameter of several $\mu$m, a hexagonal structure and showed a broad cathodoluminescence (CL) band with a peak in a range from 2.85 to 2.58 eV at 10kV and 0.5 nA. The new peaks emerged with an increase in an acceleration voltage. At 15 kV a CL band emerged and became dominant at 3.01 eV in the higher-energy region of a broad band with a peak at 2.75 eV recorded at 10 kV. We think that the peak shift is attributed to the depth profile of In content in the crystal. A sample immersed in liquid nitrogen showed a broad photoluminescence (PL) band at 2.9 eV by the excitation of a 325-nm He-Cd laser line. In the PL excitation (PLE) spectra of the 2.9 eV PL band monitored at a range from 3.26 to 3.10 eV, a peak is located at 3.47 eV, and in those from 2.95 to 2.4 eV a peak at 3.15 eV. The peak of a band shifted to 2.85 eV and its width narrowed by the PLE at 3.18 eV because the intensity of the high-energy wing reduced compared with that excited by the 325-nm line. By the excitation at 3.49 eV, the PL band shape resembled the 2.9-eV one excited by a He-Cd laser. Like the CL bands the 2.9-eV PL band consists of two bands: an emission band at around 3.4 to 3.1 eV which has a fundamental absorption as an excited state and the one at 2.85 eV which has the absorption band with the peak at 3.15 eV. We have successfully synthesized InGaN emitting blue 77K PL and RT CL emission. We observed the In related luminescence center shows a large Stokes shift and a broad bandwidth that are characteristics of a localized state.

**W11.44**
PHOTOLUMINESCENCE CHARACTERIZATION OF Mg IMPLANTED GaN. C. Ronning, H. Hofsaess, II. Physikalisches Institut, Universitaet Goettingen, Goettingen; A. Stoetzler, M. Deicher, Fakultaet für Physik, Universitaet Konstanz, Konstanz; E.P. Carlson, P.J. Hartlieb, R.F. Davis, Department of Materials Science and Engineering, North Carolina State University, Raleigh, NC.

Single crystalline (0001) gallium nitride layers, capped with a thin epitaxial aluminum nitride layer, were implanted with magnesium and subsequently annealed within the range of 300-1300 C for 10-60 minutes in vacuum. Photoluminescence (PL) measurements showed the typical donor acceptor pair (DAP) transition at 3.25 eV after annealing at high temperatures, which is related to optically active Mg acceptors in GaN. The behavior and features of this line will be presented as a function of the annealing conditions and temperature. After annealing at 1300 C an almost complete optical activation of the implanted Mg atoms was reached. This will be compared to GaN samples, which were Mg doped during growth. The results will be discussed in respect to results of other characterization methods done on implanted GaN; such as XRD, RBS and channeling. Electrical measurements were performed on these samples after removing the AlN-cap and the deposition of Pb/Au contacts. These results will also be presented.

**W11.45**
AN INVESTIGATION OF LONG AND SHORT TIME-CONSTANT PERSISTENT PHOTOCONDUCTIVITY IN UNDOPED GaN GROWN BY RF-PLASMA ASSISTED MOLECULAR BEAM EPITAXY. A.J. Ptak, V.A. Stoica, L. J. Holbert and T.H. Myers, Department of Physics, West Virginia University, Morgantown, WV.

Persistent photoconductivity (PPC) remains an issue for both doped and undoped GaN. We will present a detailed study of PPC on a set of undoped GaN samples grown by rf-plasma assisted molecular beam epitaxy which exhibit dramatically different electrical and optical properties. At least two separate PPC mechanisms with vastly different relaxation times have been identified, which can explain the wide variation in reported PPC relaxation times. PPC will be correlated with temperature dependent Hall and photoluminescence measurements. Results of spectral and frquency-dependent photoconductivity measurements yield information about below-bandgap states tentatively associated with PPC. At least one mechanism appears to rely on carrier trapping. Photo-Hall measurements have been performed to investigate the electrical nature of the capture center. This work was supported by ONR Grant N00014-96-1-1008 and monitored by Colin E. C. Wood.

**W11.46**
THE USE OF MICRO-RAMAN SPECTROSCOPY TO MONITOR HIGH-PRESSURE HIGH-TEMPERATURE ANNEALING OF ION-IMPLANTED GaN FILMS. M. Kuball, J.M. Hayes, H.H. Wills Physics Laboratory, University of Bristol, Bristol, UNITED KINGDOM; J. Jun, T. Suski, UNIPRESS, Polish Academy of Sciences, Warszawa, POLAND; H.H. Tan, J.S. Wiliams, and C. Jagadish, Department of Electronic Materials and Engineering, The Australian National University, Canberra, AUSTRALIA.

We have investigated the high-pressure high-temperature annealing of ion-implanted GaN films. The structural quality, the free carrier concentration and the strain in the implanted GaN films was monitored noninvasively during the annealing sequence using visible and ultraviolet (UV) Micro-Raman spectroscopy. The combination of UV Raman with visible Raman spectroscopy enables us to probe selectively properties of an only 40nm-thin top layer of the sample or of the entire GaN layer to gain detailed insight into the effect of the high-pressure high-temperature annealing on the ion-implanted GaN film.
Mg/P-implanted GaN films were annealed up to temperatures of 1500°C under nitrogen overpressures up to 1.6GPa. We find the nearly full recovery of their crystalline quality after anneals at 1400-1500°C. The high nitrogen overpressures prove very effective in preventing nitrogen out-diffusion from the GaN surface. We find no significant degradation effects even at the highest annealing temperatures in the GaN surface layer probed by UV Micro-Raman scattering. Strain, however, is introduced during the annealing sequence and possibly related to the inclusion of oxygen into GaN. The free carrier concentration was monitored via the $A_1(LO)$ phonon-plasmon frequency. The effect of the ion implantation on the free carrier concentration was characterized and compared with data obtained on high-pressure high-temperature annealed non-implanted GaN layers. We find an increased electron concentration after anneals at temperatures exceeding 1400°C suggesting the introduction of donors at the highest annealing temperatures.

**W11.47**
CARRIER DYNAMICS STUDIES OF THICK GaN GROWN BY HVPE. G.E. Bunea, W.D. Herzog, M.S. Ünlü, B.B. Goldberg, Boston Univ, Dept of Physics and Electrical and Computer Engineering and Photonics Center, Boston, MA; R.J. Molnar, MIT Lincoln Laboratory, Lexington, MA.

A clear understanding of recombination mechanisms in group III nitrides is essential for optoelectronics applications. Time-resolved photoluminescence (TRPL) is a powerful experimental tool to study materials because the temporal information combined with the spectral data can help determine the dynamics of the carriers involved in optical processes. We report on TRPL studies of the radiative recombination lifetime of free and bound excitons in unintentionally doped GaN grown on sapphire by hydride vapor phase epitaxy (HVPE). For a sample with low carrier concentration ($\sim 5x10^{16}$ $cm^{-3}$), low temperature time-integrated PL spectra identified the free excitons (A,B), the neutral donor bound exciton peak at $\sim$ 6 meV below, and the acceptor bound exciton peak at $\sim$ 20 meV below the free A exciton peak. The radiative recombination lifetimes were found to vary from 300 ps for $FX_A$ and 530 ps for $D^0X$ in the middle of the sample to 154 ps for $FX_A$ and 350 ps for $D^0X$ towards the edge of the sample. This may be due to spatial inhomogeneities in the sample or defects associated with dislocations. Epitaxial lateral overgrowth of GaN has attracted considerable attention recently as a method for reducing the high threading dislocations density which has limited the device performance in the nitride systems. TRPL studies are under investigation in lateral overgrowth GaN grown by HVPE, in order to determine the influence of these defects on the carrier lifetimes and recombination mechanisms.

**W11.48**
FUNDAMENTAL EXCITONIC PARAMETERS OF GaN. M. Dietrich, A. Göldner, A. Hoffmann, and I. Broser, Department of Physics, Technical University of Berlin, Berlin, GERMANY.

For optoelectronic applications in the green, blue and UV spectral region GaN and its ternary and quaternary alloys became a main suitable material system of semiconductors. To improve devices like blue and green lasers and LEDs enhancing the quantum efficiency of the light emitting processes is a essential method. On this basis, we present a theoretical and experimental optical study of free excitons in wurzite GaN. By using optical reflectance measurements the structures of free exciton states of GaN-layers are investigated depending on the angle of incidence of the incoming light, the axis of the electrical field, and the c-axis. In connection with theoretical calculations of a multi oscillator model under consideration of spatial dispersion, an exciton-free layer, and additional boundary conditions (abc's) dielectrical functions of GaN could be determined in both configurations, perpendicular and parallel to the c-axis. Additionally, the used theoretical model provides beside other parameters like the damping constant as a mean for the crystal quality also the longitudinal-transversal-splitting of the excitons ($\omega_{LT}$). This value is directly correlated to the oscillator strength of the resonances. Moreover, we used a further experimental method to investigate the oscillator strength: the calorimetric absorption spectroscopy (CAS). This method enables us to detect directly the nonradiative relaxation of the crystal which dominates the lifetime of the respective resonances and therefore, their oscillator strengths. Furthermore, quantum efficiencies of the states in the bandgap region are determined by using the CAS-setup. Results of these measurements show a limitation of the quantum efficiency near the bandgap by approximately 30%.

**W11.49**
PRISM COUPLING AS A NONDESTRUCTIVE TOOL FOR THE OPTICAL CHARACTERIZATION OF GALLIUM NITRIDE AND RELATED SEMICONDUCTING COMPOUNDS. El Hadj Dogheche, Brahim Belgacem and D. Remiens, Laboratoire des Materiaux Avances Ceramiques (LAMAC) - Universite de Valenciennes et du hainaut-Cambresis Le Mont-Houy, Valenciennes, FRANCE; Pierre Ruterana, Laboratoire d'Etudes et de Recherches sur les Materiaux, UPRESA 6004, ISMRA, Caen, FRANCE; F. Omnes, CRHEA-CNRS, Sophia-Antipolis, Valbonne, FRANCE.

In this work, the optical properties of AlGaN thin films grown metalorganic vapor phase epitaxy have been investigated using a guided-waves technique based on the prism coupling. The results reported demonstrate the usefulness and the accuracy of such a method for simultaneously determining the film thickness and the refractive indices. Highly precise values of the refractive indices (n) and their dependence on the alloys composition (x) were reported for $Al_xGa_{1-x}N$ structures. A relationship was therefore established. Moreover, the composition of the alloys could be accurately obtained using optical data by generating a calibration curve between (n) and (x). In order to analyze the homogeneity of the films and the film - substrate interface, we have reconstructed the refractive index profiles directly from the knowlegde of optical informations. In some cases, we have observed essential changes in the index profiles, this was attributed to the presence of structural defects near the interface. Conventional as well as high resolution electron microscopy was carried out on the same samples whose Al content varied from 5 to 3%. A highly defective zone closeto the interface was identified in agreement with the optical measurements. It is demonstrated that these non destructive optical measurements are very sensitive to the defects inside the layers.

**W11.50**
DEEP LEVEL RELATED YELLOW LUMINESCENCE IN p-TYPE GaN GROWN BY MBE ON (0001) SAPPHIRE. Nicola Armani, Giancarlo Salviati, Carlo Zanotti-Fregonara, CNR-MASPEC Inst., Dept. of Physical and Structural Properties of Electronic Materials, Parma, ITALY; Enos Gombia, CNR-MASPEC Inst., Dept. of Physics of Semiconductors, Parma, ITALY; Martin Albrecht, Horst Strunk, Erlangen Univ., Electron Microscopy Dept., Erlangen, GERMANY; Markus Mayer, Markus Kamp, Ulm Univ., Electronics Dept., Ulm, GERMANY.

The broad yellow emission (YL) in MBE grown p-type GaN layers doped with Mg concentrations ranging from $10^{16}$ to $10^{19}$ $cm^{-3}$ was studied by spectral CL (T=5K), TEM and DLTS. The emission was explained suggesting a different mechanism could be responsible for the YL in p-type GaN with respect to that acting in n-type GaN. CL spectra showed transitions at 2.2, 2.8, 3.27, 3.21(ZB-BX) and 3.46(WZ-BX) eV. TEM evidenced a cubic phase whose amount increased by increasing the Mg concentration in the layers. By approaching the layer/substrate interface, nano tubes with a density of $3\times10^9$ $cm^{-2}$ were observed. Besides this, coherent inclusions were found with a diameter in the nm range and a volume fraction of about 1%. The 2.8 eV transition was correlated to a deep level at 600 meV below the CB due to $Mg_{Ga}$-$V_N$ complexes; the 3.27 eV emission was ascribed to a shallow acceptor at about 220 meV above the VB due to $Mg_{Ga}$. The 2.2 eV yellow band was not present in undoped samples and increased by increasing the Mg concentration. It was ascribed to a transition between a deep donor level at 0.8-1.1 eV below the CB edge due to $N_{Ga}$ and the shallow acceptor due to $Mg_{Ga}$. This assumption was checked by studying the role of C in the Mg compensation. CL spectra from an heavely C contaminated sample showed transitions between a C-related 300 meV shallow donor and a deep acceptor level at about 0.9-1.1 eV above the VB due to a $N_{Ga}$-$V_N$ complex. In our hypothesis this should induce the decrease of the integrated intensity of both the 2.2 and 2.8 eV bands, as actually shown by CL investigations. Finally, the presence and nature of deep levels was also studied by DLTS investigations whose results were consistent with the CL data.

**W11.51**
AN STUDY OF ANNEALED GaN GROWN BY MOLECULAR BEAM EPITAXY USING PHOTOLUMINESCENCE SPECTROSCOPY. Abigail Bell, Dimitris Korakakis, Univ of Nottingham, School of Physics and Astronomy and School of Electrical and Electronic Engineering, Nottingham, UK; Ian Harrison, Eric Larkins, Univ of Nottingham, School of Electrical and Electronic Engineering, Nottingham, UK; Jonathan Hayes, Martin Kuball, Univ of Bristol, H.H. Wills Physics Laboratory, Bristol, UK.

Photoluminescence (PL) spectroscopy has been used to investigate the effect of annealing molecular beam epitaxially grown GaN in different ambients. By observing the changes in the PL spectra as a function of ambient temperature and gas used, important information concerning the origin of defects within GaN has been found. Samples were annealed in different atmospheres, (including oxygen, oxygen and water vapour, nitrogen and argon) and at different temperatures. The region in the PL between 2.0eV and 2.8eV which contains the peak commonly referred to as Yellow Luminescence was studied. In this study peaks appeared at approximately 2.3eV and 2.6eV, some what higher than the usual yellow luminescence peak. We find that the 2.6eV peak is dominant for high annealing temperatures and the 2.3eV peak dominates at low annealing temperature for the samples annealed in oxygen. When annealed in argon and nitrogen the 2.6eV peak dominates at all annealing temperatures. Changes in the PL spectra between anneals were also seen in the 3.24eV region, this luminescence has previously been attributed to oxygen impurities acting as a so called shallow-deep-level in the material. By annealing in different ambients we hope to introduce different defects in the material and therefore investigate the origin of the peak. We also studied the shift in the donor bound exciton ($D^\circ X$) peak which is attributed to changes in stress of the sample upon annealing. The samples annealed in oxygen exhibited a shift to higher energy with increasing annealing temperature from 800°C to 1000°C. However, further increasing the annealing temperature to 1100°C caused less of a shift. The assignment of an increase in stress has been confirmed by Raman spectroscopy.

**W11.52**
NON-LINEAR OPTICAL CHARACTERIZATION OF GaN LAYERS GROWN BY MOCVD ON SAPPHIRE. I.M. Tiginyanu, Technical Univ of Moldova, Chisinau, MOLDOVA; I. Kravetsky, Institute of Applied Physics, Chisinau, MOLDOVA; D. Pavlidis, A. Eisenbach, Univ of Michigan, Dept of Electrical Engineering and Computer Science, Ann Arbor, MI; R. Hildebrandt, G. Marowsky, Laser-Laboratorium Goettingen e.V., Goettingen, GERMANY; H.L. Hartnagel, Technical Univ, Darmstadt, GERMANY.

In spite of a huge lattice mismatch (13%) between GaN and sapphire, the use of a low temperature buffer layer makes it possible to grow device-quality GaN layers by MOCVD. In this report we present experimental evidence that optical second and third harmonic generation (SHG and THG) techniques provide valuable information concerning the crystalline structure of GaN films grown on sapphire substrates. Both a Q-switched Nd-YAG laser (1064 nm) and an optical parametric oscillator (450 - 800 nm) were used as pump beam sources. The dependence of SHG, measured in transmission geometry, upon the sample rotation angle about vertical axis normal to the fundamental laser beam showed the c-textured growth of GaN epilayers on sapphire. The SHG polarization dependence as well as the intensities of both SHG and THG were found to be sensitive to the orientation of the sample (front and back sides) in respect to the incident fundamental beam. Fine oscillations like Fabry-Perot modes were observed in measured SHG and THG angular dependencies. The effective values of non-linear optical susceptibility coefficients for GaN layers were estimated in respect to the z-cut quartz. The obtained results are explained taking into account the contribution of two GaN films possessing different microstructures and residual strains to the non-linear optical response.

**W11.53**
RADIATIVE RECOMBINATION BETWEEN TWO DIMENSIONAL ELECTRON GAS AND PHOTOEXCITED HOLES IN MODULATION DOPED AlGaN/GaN HETEROSTRUCTURES. Bo Shen, Takao Someya, Osamu Moriwaki, Yasuhiko Arakawa, Institute of Industrial Science, Univ of Tokyo, JAPAN.

The photoluminescence (PL) related to the recombination of two dimensional electron gas (2DEG) in AlGaAs/GaAs heterostructures has been studied extensively, which is denoted as the H-band. The H-band is only observed at temperatures lower than 14 K. However, little research has been carried out on the optical properties of AlGaN/GaN heterostructures until now. Due to the large discontinuity of the conduction bands and strong piezoelectric polarization in AlGaN/GaN heterostructures, the PL related to the 2DEG at AlGaN/GaN heterointerfaces is expected to be observed at temperatures much higher than 14 K. In this study, PL spectra of the modulation doped AlGaN/GaN heterostructures were investigated. The samples were grown using atmospheric pressure metal organic chemical vapor deposition. The Al molar fraction in the AlGaN barrier is 0.15. The PL intensity was enhanced by incorporating a thin AlGaN layer with the Al molar fraction of 0.07 into the GaN layer to suppress the diffusion of photoexcited holes. The PL peak related to the recombination between the 2DEG and photoexcited holes at the heterointerfaces is located at 3.4480 eV at 40 K, which is 45.2 meV lower than that of the free excitons (FE) emission in GaN. The peak can be observed at the temperature as high as 80 K. The energy distance between the PL peak related to the 2DEG and the FE emission increases with increasing temperature. Meanwhile, the peak energy increases roughly linearly with the logarithm of the excitation intensity. It is attributed that the screening effect of electrons on the bending of the conduction band at the heterointerface increases as temperature or the excitation intensity is increased.

**W11.54**
SPECTROSCOPIC ELLIPSOMETRY ANALYSIS OF InGaN/GaN AND AlGaN/GaN HETEROSTRUCTURES USING A PARAMETRIC DIELECTRIC FUNCTION MODEL. J. Wagner, A. Ramakrishnan, H. Obloh, M. Kunzer, K. Koehler, Fraunhofer-Institut fuer Angewandte Festkoerperphysik, Freiburg, GERMANY; B. Johs, J. A. Woollam Co., Inc., Lincoln, NE.

Reproducible growth of high-quality (AlGaIn)N heterostructures requires, because of the rather narrow growth parameter window, fast and efficient characterization of, e.g., layer thickness and composition. Spectroscopic ellipsometry (SE) is a nondestructive optical characterization technique which has been applied successfully to the analysis of conventional III-V heterostructures, including in-situ monitoring of epitaxial layer growth. Concerning group III nitrides SE has been used so far only to study bulk-like GaN, AlGaN, and InGaN layers [1]. The aim of the present investigation was therefore to apply variable angle SE to the characterization of GaN/AlGaN/GaN heterostructures and InGaN/GaN quantum wells (QWs). The resulting pseudodielectric function spectra were analyzed using a multilayer approach, describing the dielectric functions of the individual layers by a parametric dielectric function model [2]. In the dielectric function spectrum of InGaN/GaN QWs the fundamental band gap resonance of the InGaN was found to broaden for QW widths around 10 nm, as compared to bulk-like InGaN layers, due to piezoelectric field effects. For much smaller well widths of typically 2 nm, however, quantum confinement was found to dominate over piezoelectric field effects, resulting in a much narrower band gap resonance accompanied by an increase in oscillator strength. Finally the model dielectric functions derived here for GaN, AlGaN, and InGaN have been used for a modeling and quantitative analysis of the pseudodielectric function spectra of complete LED and waveguide structures.
[1] T. Kawashima, et al., J. Appl. Phys. 82, 3528 (1997); G. Yu, et al., Appl. Phys. Lett. 70, 3209 (1997); J. Wagner, et al., Appl. Phys. Lett. 72, 1715 (1998).
[2] C.M. Herzinger, et al., J. Appl. Phys. 77, 4677 (1995); ibid. 79, 2663 (1996).

**W11.55**
PICOSECOND PHOTOINDUCED REFLECTIVITY STUDIES OF GaN PREPARED BY LATERAL EPITAXIAL OVERGROWTH. M. Wraback, H. Shen, Army Research Laboratory, Sensors and Electron Devices Directorate, Adelphi, MD; C.J. Eiting, J.C. Carrano and R.D. Dupuis, Microelectronics Research Center, The University of Texas at Austin, Austin, TX.

We investigated room-temperature carrier dynamics in GaN prepared by lateral epitaxial overgrowth (LEO) through measurement of the photoinduced change in reflectivity on a picosecond time scale. The sample employed in this study was a $\sim$5 $\mu$m-thick undoped GaN LEO film grown by MOCVD upon 15 $\mu$m-wide $SiO_2$ stripes patterned with 3 $\mu$m windows between the stripes. The photoluminescence peak for this sample was at 3.427 eV (362 nm). Frequency degenerate pump and probe measurements were performed using a tunable source of ultraviolet pulses of $\sim$150 fs duration. In all cases a positive, pulse-width-limited rise in the change in probe reflectivity $\Delta$R associated with pump-induced bleaching is observed at zero time delay. For excitation at 364.5 nm, the $\Delta$R decay at low pump intensity is biexponential in nature, possessing a 700 ps component that is about four times greater than the 50 ps component. Noting that the spot size of the probe is $\sim$100 $\mu$m in diameter, comparison of the ratio of decay components with the ratio of stripe size to window size suggests that the slow decay may represent the lifetime of cold excitons in the LEO material, while the fast decay may be characteristic of the highly defective window region. For 357.5 nm excitation, the strong increase in decay rate with decreasing intensity suggests that screening of the Coulomb interaction by a cold electron-hole plasma may play an important role in the carrier relaxation process. For 347 nm excitation, hot carrier relaxation is probed, and an ultrafast ($\sim$ 1 ps) decay becomes prominent as the excitation density is lowered to $\sim 10^{18} cm^{-3}$. When the carrier density is halved again, this decay disappears, suggesting that the screening of the electron-LO phonon interaction may be reduced enough that the initial relaxation process becomes faster than the temporal resolution of our experiment.

**W11.56**
CORRELATION OF MID-GAP OPTICAL EMISSION AND MOBILITY DEGRADATION IN HOMOEPITAXIAL GAN WITH IONIZED NITROGEN FLUX. A.P. Young, L.J. Brillson, Dept of Electrical Engineering, The Ohio State University, Columbus, OH; Yoshiki Naoi, Dept of Electrical and Electronic Engineering, The University of Tokushima, Tokushima, JAPAN; C.W. Tu, Dept of Electrical Engineering, University of California, San Diego, CA.

GaN-based material systems are critically dependent upon control of point defects for use in high speed transport and optical devices. Considerable debate continues on whether native defects or impurities are responsible for mid-gap emission in GaN. We have established a correlation between states responsible for such mid-gap emission and film mobility by homoepitaxial growth under different nitrogen growth conditions. Specimens were grown via molecular beam epitaxy (MBE) on GaN/sapphire composite substrates using an RF plasma for the nitrogen source. By imposing a deflector voltage at the tip of the plasma source, we varied the ion/neutral flux ratio to determine how N ions affect mid-gap luminescence. Ion deflector voltages of 0 V, 500 V, and 700 V yielded specimen Hall mobilities of 300, 500, and 640 $cm^2$/V-sec, respectively. Low energy electron-excited nanoluminescence (LEEN) spectroscopy in ultrahigh vacuum showed corresponding mid-gap emission intensities in the bulk (3 keV incident energy, 30 nm probe depth) that decreased in the ratio 50 : 1.3 : 1 with increasing deflector voltage. Near band edge emission (NBE) at 3.42 eV increased as the mid-gap emissions at 1.8, 2.2, and 2.38 eV decreased. Energy-dependent LEEN spectra revealed a depth dependence to this defect emission. In all three cases, mid-gap emission exceeded NBE emission at the surface (500 V incident

energy, 4 nm probe depth). The contrast in mid-gap vs. NBE emission is significantly lower at depths below 30 nm, comparable to the penetration depth of a He-Cd laser (ca. 50 nm). Also, the gap emissions exhibit oscillations indicative of nm-smooth interfaces, as confirmed by atomic force microscopy. LEEN spectral features alone demonstrate the primary role of native defects, not impurities, in the mid-gap emissions. Furthermore, the correlation of mid-gap spectral emission with mobility indicates the dominant effect such defects have on overall transport properties.

**W11.57**
DYNAMICS OF ANOMALOUS TEMPERATURE-INDUCED EMISSION SHIFT IN MOCVD-GROWN (Al, In)GaN THIN FILMS. Yong-Hoon Cho, G.H. Gainer, J.B. Lam, J.J. Song, Oklahoma State Univ, Center for Laser and Photonics Research and Dept of Physics, Stillwater, OK; W. Yang, Honeywell Technology Center, Plymouth, MN; W. Jhe, Seoul National University, Center for Near-field Atom-photon Technology and Dept of Physics, Seoul, KOREA.

We present a comprehensive study of the optical characteristics of (Al, In)GaN epilayers measured by photoluminescence (PL), PL excitation, and time-resolved PL spectroscopy. By studying alloy epilayers, we minimized ambiguous effects typical of quantum structures, such as strain-induced piezoelectric polarization, quantum confinement, layer thickness variations, and interface-related defects. For not only InGaN, but also AlGaN epilayers with large Al content, we observed an anomalous PL temperature dependence: (i) an "S-shaped PL" peak energy shift (decrease-increase-decrease) and (ii) an "inverted S-shaped" full width at half maximum (FWHM) change (increase-decrease-increase) with increasing temperature. The thermal decrease in integrated PL intensity was suppressed and the effective lifetime was enhanced in the temperature region showing the anomalous temperature-induced emission behavior, reflecting superior luminescence efficiency due to the suppression of non-radiative processes. From the time-resolved PL results, together with the S shape (inverted S shape) of the PL peak position (FWHM) as a function of temperature and the much smaller PL intensity decrease in the temperature range showing the anomalous emission behavior, we conclude that strong localization of carriers occurs in InGaN and even in AlGaN with rather high Al content. The following characteristics increase with increasing Al content in the AlGaN epilayers: (i) a Stokes shift between the PL peak energy and the absorption edge, (ii) a redshift of the emission with decay time, (iii) the deviations of the PL peak energy, FWHM, and PL intensity from their typical temperature dependence, and (iv) the corresponding temperature range of the anomalous emission behavior. This indicates that the band-gap fluctuation responsible for these characteristics is due to energy tail states caused by non-random inhomogeneous alloy potential variations enhanced with increasing Al content.

**W11.58**
TIME-RESOLVED SPECTROSCOPY OF InGaN. Milan Pophristic, Frederick Long, Rutgers University, Dept of Chemistry, Piscataway, NJ; Chuong Tran, EMCORE Corp., Somerset, NJ.

We have used time-resolved photoluminescence to examine $In_xGa_{1-x}N$/GaN light-emitting diodes (LEDs) before the final stages of processing at room temperature. We have found dramatic differences in the time-resolved kinetics between dim, bright and super bright LEDs. The lifetime of the emission for the dim LED is quite short, 110 ± 20 ps at PL maximum, and the kinetics are not dependent upon wavelength. In contrast for the bright and superbright LEDs, the kinetics are clearly wavelength dependent, highly non-exponential, and are on the nanosecond time scale (lifetimes are in order of 1 ns for bright and 10 ns for super bright LED at the PL max). Such long times are in agreement with prediction of exciton localization, and importance of localization in radiative processes. The photoluminescence kinetics can be described by a stretched exponential function, indicating significant disorder in the material. The disorder is attributed to spatial fluctuations of the local indium concentration. Longer photoluminescence lifetimes are observed for blue/green LEDs. This is consistent with increased indium alloy fluctuations and subsequent localization in these materials. We have also used time-resolved emission to measure carrier diffusion in the p-type GaN region of the LED.

**W11.59**
MIXED COLOR EMISSION FROM GaN CO-DOPED WITH $Er^{3+}$ AND $Eu^{3+}$ OR $Tm^{3+}$. D.S.Lee, R. Birkhahn, M. Garter, J. Heikenfeld, A.J. Steckl, Nanoelectronics Laboratory, University of Cincinnati, OH.

Rare earth (RE) doped semiconductors have been studied because of their suitability for optoelectronic devices. Interest in RE doped GaN has increased to develop novel electroluminescence (EL) devices which combine the advantages of GaN as a host material and unique luminescence characteristics of RE ions. GaN has the advantage of minimal thermal quenching of optical properties while the RE ions emit at wavelengths which are independent of the host material. We have previously reported visible color emission from a single RE-doped into GaN: $Er^{3+}$ shows two green emission lines at 537 nm and 558 nm; $Pr^{3+}$ shows red at 650 nm; $Tm^{3+}$ shows blue at 480 nm; $Eu^{3+}$ shows red at 620 nm and several minor lines. For this abstract, we report the mixed color emission of GaN films co-doped with Er and Eu or with Tm by both EL and photoluminescence (PL). RE co-doped GaN films were grown by solid source MBE on Si (111) substrates using solid sources (for Ga, Er, Eu and Tm) and a plasma gas source for $N_2$. $Er^{3+}$ and $Tm^{3+}$ ions doped into $\alpha$-GaN thin films emit light in the visible (green and blue, respectively) corresponding to $Er^{3+}$ and $Tm^{3+}$ atomic transitions in the rare earth atom. Simple Schottky devices were fabricated on these films and the device characteristics studied. The resulting color was an aqua or turquoise as perceived by the eye and nearly invariant to applied voltage and normal operating temperatures. Similar results were obtained with GaN co-doped with $Er^{3+}$ and $Eu^{3+}$. PL measurements demonstrate that the relative intensity of the green emission of $Er^{3+}$ to the red emission of $Eu^{3+}$ increases linearly with $Er^{3+}$ concentration using a fixed $Eu^{3+}$ concentration. By varying the relative concentrations of the REs doped into GaN in this manner, we predict that any color in the visible spectrum is achievable.

**W11.60**
THERMAL-ANNEALING-ACTIVATED UPCONVERSION LUMINESCENCE FROM FIB-IMPLANTED GaN FILMS. L.C. Chao, B.K. Lee, C.J. Chi, J. Cheng, A.J. Steckl, Nanoelectronics Laboratory, University of Cincinnati, Cincinnati, OH.

Rare earth ions have been widely doped into insulators such as fluoride and oxide compounds for laser and optical communication applications. Among the rare earths, erbium and praseodymium have drawn the most interest because of the $Er^{3+}$ emission at 1.54 $\mu$m and $Pr^{3+}$ emission at 1.3 $\mu$m, which correspond to wavelengths for minima in absorption and dispersion of silica optical fibers. If sufficient light emission can be obtained from rare-earth-doped semiconductors, monolithic optoelectronic devices will be realized which will greatly simplify and reduce the cost of modern optical communication systems. Recently visible and/or infrared emission have been obtained from a variety of erbium doped WBGS materials, such as SiC, GaAs, InP and GaN. Among them, GaN has drawn the most attention. To date, photoluminescence (PL), electroluminescence (EL) and cathodoluminescence (CL) have been obtained from Pr, Eu, Dy, Er, and Tm doped GaN. This indicates that GaN is an excellent host for the incorporation of rare earth elements. We report green upconversion luminescence from FIB Er-implanted GaN films after annealing. We have investigated both furnace (FA) and rapid thermal (RTA) annealing under different ambients at a temperature of 1100°C. We have studied the effect of proximity caps ($SiO_2$, $Al_2O_3$), as well as capless annealing. For example, GaN samples at 1100°C for one hour exhibited strong green upconversion at 523 nm and 546 nm under red (840nm) and infrared (1.0 $\mu$m) excitation. Upconversion intensity was measured for Er doses ranging from $4.3\times10^{12}$ to $2.4\times10^{16}$ atoms/cm$^2$. Maximum upconversion intensity at 546 nm was observed at a dose of $1\sim2\times10^{15}$ atoms/cm$^2$, which corresponds to an atomic percentage of 0.3∼0.6%. RTA was used to minimize surface roughness while maintaining strong green luminescence. The upconversion spectra of FIB Er-implanted GaN samples after RTA indicate a better crystalline structure is preserved while erbium ions are optically activated. AFM and SEM are used to study surface morphology. Upconversion mechanisms are determined by measuring upconversion luminescence intensity against excitation laser power.

**W11.61**
Ga AND Er SITE COMPETITION IN GaN:Er FILMS EXHIBITING VISIBLE LUMINESCENCE. R. Birkhahn, J. Heikenfield, M. Garter, D.S. Lee and A.J. Steckl, University of Cincinnati, Nanoelectronics Laboratory, Cincinnati, OH; P.H. Citrin and P.A. Northrup, Lucent Technologies, Bell Laboratories, Murray Hill, NJ; K. Lorenz and R. Vianden; ISKP, University of Bonn; M.F. da Silva, J.C. Soares, E. Alves, ITN, Sacavém, PORTUGAL; A. Saleh, Charles Evans and Associates, Sunnyvale, CA; J.M. Zavada; European Research Office, London, UNITED KINGDOM.

The recent discovery that GaN doped with Er emits visible as well as the usual infrared (1.54 $\mu$m) luminescence has prompted an investigation into the lattice location of the Er atoms. Such a study is intended to further the understanding of both materials issues (e.g., improving the efficiency of Er incorporation) and fundamental questions regarding the energy transfer mechanism between host and rare earth (RE). There may also be implications to other REs incorporated into GaN and other wide-bandgap semiconductors such as SiC and ZnS. Indeed, we have already observed similar visible (and infrared) luminescence involving RE 4*f* transitions in GaN:Er (green), GaN:Pr (red), GaN:Tm (blue and red), and GaN:Eu (blue through red). All of these systems luminesce under both optical and electrical

pumping. The GaN:Er films were produced by MBE with a nitrogen plasma source and solid sources for Ga and Er. Since the visible luminescence was observed from samples prepared using a wide range of Er fluxes and substrate growth temperatures, we focused our study on the role of Ga flux in controlling Er incorporation and lattice location. The Er concentration was determined by secondary ion mass spectrometry, and the lattice location was determined using channeling Rutherford backscattering and extended x-ray absorption fine structure measurements. Films with optimum optical properties clearly showed that the Er ions occupy substitutional Ga sites. Our results also show that the concentration of Er incorporated into the GaN films is controlled by not only the flux of Er but also the flux of Ga, indicative of site competition during growth.

**W11.62**
EFFECT OF ANNEALING AND CODOPING ON THE PL INTENSITY FROM Er-DOPED GaN. M.E. Overberg, J.D. MacKenzie, C.R. Abernathy, S.J. Pearton, University of Florida, Dept of Materials Engineering, Gainesville, FL.

An attractive alternative for 1.54 $\mu$m heterojunction semiconductor lasers are Er doped semiconductors, whose emission wavelength is host-material insensitive. III-nitrides are particularly attractive for this application as their wide bandgaps help to reduce thermal quenching of the $Er^{+3}$ emission, allowing operation at room temperature. GaN is an attractive choice due to its good mechanical properties and ability to be electrically doped (over other III-nitrides). The contribution of other impurities such as C and H is expected to play and important role in the emission process. In AlN, it has been shown that hydrogenation of Er-doped material was effective in increasing the 1.54 $\mu$m luminescence intensity by as much as a factor of 5. Previous results have indicated that variations in the C background in GaN can increase the Er optical activation and suppress the thermal quenching behavior. In this study the effect of H annealing on the luminescence intensity from Er-doped GaN has been investigated by both rapid thermal annealing and annealing under an $H_2$ plasma in UHV. Unlike AlN, hydrogenation of GaN:Er appears to produce a marked reduction in the room temperature PL intensity. Annealing under nitrogen ambient does not produce such behavior suggesting that the formation of a hydrogen-containing complex is responsible for this behavior. The hydrogenation effects of material codoped with C will also be reported in regard to both luminescence and the degree of thermal quenching.

**W11.63**
CATHODOLUMINESCENCE SPECTROSCOPY OF ERBIUM DOPED GALLIUM NITRIDE GROWN ON SILICON BY MBE AND MOMBE. S.H. Goss, L.J. Brillson, Center for Materials Research, The Ohio State University, Columbus, OH; J.D. MacKenzie, C.R. Abernathy, Dept of Materials Science and Engineering, University of Florida, FL.

Er-doped GaN commands considerable research attention due to its utility as an infrared source and amplifier in the minimum loss region of optical fibers. Substrates for GaN that are more conductive than sapphire yet less expensive than SiC are needed to facilitate commercially viable devices. Silicon substrates may offer such an alternative, but it is not yet known how the severe lattice mismatch and associated defects will affect GaN:Er's optical emission properties. We have used low energy electron-excited nanoluminescence (LEEN) spectroscopy to compare the optical properties of GaN:Er grown on silicon either by molecular beam epitaxy (MBE) or metal organic (MO) MBE. The specimens examined were ~500 nm thick films grown on Si (100) substrates with an Er concentration of ~3e18$cm^{-3}$. For the MBE-grown GaN case, the carbon and oxygen impurity concentrations were 1e19 $cm^{-3}$, while the impurity level in the MOMBE-grown specimen was a factor of ten higher. We measured four Er-related peaks in the LEEN spectra at 0.8, 1.8, 2.25, and 2.4 eV, in addition to the GaN near band edge (NBE) emission at 3.4 eV. LEEN spectra obtained as a function of incident beam energy yield probe depths ranging from 5 to 130 nm. Er emission decreases with decreasing probe depth, correlated with a high surface carbon concentration as identified by Auger electron spectroscopy (AES) for both samples. Furthermore, the Er peak emission intensities increase with annealing by a factor of 70 for samples annealed to 1000 °C. The resultant emission intensities are up to seven times greater than those achieved on sapphire substrates. In addition, measurements of MBE vs. MOMBE GaN:Er show that additional C and O impurities have only reduced already intense optical emission at 0.8 eV by a factor of two, highlighting the potential use of this material for future applications.

**W11.64**
PHOTOLUMINESCENCE AND CATHODOLUMINESCENCE OF GaN DOPED WITH Pr. W.M. Jadwisienczak, H.J. Lozykowski, School of Electrical Engineering & Computer Science, and Condensed Matter & Surface Sciences Program, Ohio University, Stocker Center, Athens, OH; I. Brown Lawrence Berkeley Laboratory, University of California at Berkeley, Berkeley, CA.

In this work we studied the cathodoluminescence (CL) and photoluminescence (PL) and their kinetics of GaN implanted with praseodymium. The GaN: $Pr^{3+}$ luminescence spectra as well as the kinetic processes were investigated using as excitation sources $N_2$, He-Cd lasers, and CL beam pulsing electron gun system EK-2035-R as a function of temperature and excitation intensity. Richly structured CL and PL luminescence spectra attributed to trivalent praseodymium ion are resolved over the wide spectral range from 400 nm to 1000 nm without emission from a GaN host. The rise and decay kinetics as a function of temperature were analyzed on the basis of a proposed model. The temperature dependence of the decay rates shows that relaxation occurs mainly by high energy optical phonons The transition energies of $Pr^{3+}$ are well known from other host crystals and are therefore assigned to transitions observed in our spectra. The CL and PL are strong over the temperature range from 11K to 330K. The results indicate that rare earth doped GaN epilayers are suitable as a material for visible optoelectronic devices.

**W11.65**
COMPARISON OF THE OPTICAL PROPERTIES OF ERBIUM DOPED GALLIUM NITRIDE PREPARED BY METALORGANIC MOLECULAR BEAM EPITAXY (MOMBE) AND SOLID SOURCE MOLECULAR BEAM EPITAXY (SSMBE). U. Hömmerich, J.T. Seo, Hampton University, Dept. of Physics, Hampton, VA; J.D. MacKenzie, C.R. Abernathy, Univ. of Florida, Dept. of MS&E, Gainesville, FL; R. Birkhahn, A.J. Steckl, Univ. of Cincinnati, Nanoelectronics Lab, Cincinnati, OH; J.M. Zavada, European Research Office, London, UNITED KINGDOM.

The visible and infrared luminescence from rare earth doped GaN is of significant current interest for potential applications in optical communications and full color displays. Electroluminescence at 413 nm, 537 nm, 558 nm, 670 nm, 1000 nm and 1540 nm has been reported from in-situ doped GaN:Er. Interestingly, the incorporation and optical activation of rare earth ions in GaN seems strongly dependent on the preparation method. In this paper we present a comparison of the optical properties of Er doped GaN prepared by MOMBE and SSMBE. GaN:Er prepared by MOMBE exhibited strong 1540 nm luminescence under below-gap excitation. However, for above-gap excitation a greatly reduced Er luminescence intensity was observed. For GaN:Er prepared by SSMBE the situation was reversed and a strong infrared emission was found under above-gap excitation. In addition, this sample also emitted green luminescence lines at around 550 nm. Details of the absorption and emission properties of both samples will be discussed at the conference.

**W11.66**
$Cl_2$/Ar HIGH DENSITY PLASMA DAMAGE IN GaN SCHOTTKY DIODES. A.P. Zhang, G. Dang, F. Ren, University of Florida, Dept of Chemical Engineering, Gainesville, FL; X.A. Cao, H. Cho, E.S. Lambers, S.J. Pearton, University of Florida, Dept of Materials Science and Engineering, Gainesville, FL; R.J. Shul, L. Zhang, A.G. Baca, Sandia National Laboratories, Albuquerque, NM; R. Hickman, J.M. Van Hove, SVT Associates, Eden Prairie, MN.

GaN-based electronics offer the potential of high frequency operation at elevated temperature(500°C) and high power levels than conventional GaAs or Si devices. Precise pattern transfer during fabrication of those devices requires use of dry etching method with relatively high ion energy in order to break the strong Ga-N bond (8.92 eV/atom), which causes some ion-induced damage and possibility of a non-stoichiometric near-surface region due to preferential loss of $N_2$. To date there has been relatively little work on understanding the effect of plasma processes on the electrical characteristics of GaN. In this study, we report the result of the effects of $Cl_2$/Ar Inductively Coupled Plasma (ICP) exposure on GaN Schottky diodes and process procedures to remove the plasma damage. Exposure in $Cl_2$/Ar discharges produces reductions in both reverse breakdown voltage($V_B$) and Schottky barrier height ($\phi_B$). The extent of these reduction is a function of both ion energy and ion flux. Two different post-etch treatments were performed in an attempt to remove the ion-damaged GaN surface layer, namely annealing in $N_2$ or UV-ozone oxidation followed by dissolution of the oxide. We investigate the effects of UV/ozone time, anneal temperature, anneal time and HCl concentration. There are ~40% recovery in $V_B$ and ~20% in $\phi_B$ respectively for the UV/ozone time up to 5 min, but there is no further improvement for longer time. For the anneal temperature, there is a ~50% recovery in $V_B$ for anneals in the range of 500-700°C, and little change thereafter. At fixed temperature 700°C, the improvement in both parameters($V_B$ and $\phi_B$) leads to saturation beyond 60 sec. Use of a stronger HCl solution (~38%) also improves the VB value compared to use of the 1:20 solution. All treatments provide only partial restoration of the diode properties. To establish the chemical state and roughness of the GaN

surface at different stages, AES and AFM also were performed. The degradation mechanism appears to be creation of a conducting, non-stoichiometric ($N_2$-deficient) near surface region on the GaN.

**W11.67**
PROCESSING AND DEVICE PERFORMANCE OF GaN POWER RECTIFIERS. X.A. Cao, S. J. Pearton, University of Florida, Department of Materials Science and Engineering, Gainesville, FL; G.T. Dang, A.P. Zhang, F. Ren, University of Florida, Department of Chemical Engineering, Gainesville, FL; J. Han, Sandia National Laboratories, Albuquerque, NM; J.-I. Chyi, C -M. Lee, C.-C. Chuo, National Central University, Department of Electrical Engineering, Chung-Li, TAIWAN; G.-C. Chi, National Central University, Department of Physics, Chung-Li, TAIWAN; S.N.G. Chu, Bell Laboratories, Lucent Technologies, Murray Hill, NJ; R.G. Wilson, Consultant, Stevenson Ranch, CA.

Planar- and mesa-geometry GaN Schottky diode rectifiers have been fabricated on a variety of MOCVD grown layers (3-11 $\mu$m thick). Similar reverse breakdown voltages can be obtained in both geometries provided that dry etch sidewall damage is removed by annealing in $N_2$ or hot etching in NaOH. Values for the figure of merit $V_{RB}{}^2/R_{ON}$ of $>$4.5 MW$\cdot$cm$^{-2}$ were achieved at 25 °C. Ratios of blocking voltage to forward voltage drop of $\sim$100:1 were obtained. The $V_{RB}$ values for GaN are still about a factor of 2-3 lower than predicted theoretically for the doping and epi layer thickness used. A comparison of different edge termination techniques (implant, dielectric passivation, guard-ring) for improving $V_{RB}$, and the resultant effect on the temperature coefficient for $V_{RB}$ will be presented.

**W11.68**
OXYGEN IMPLANT ISOLATION OF n-GaN FIELD-EFFECT TRANSISTOR STRUCTURES. G. Dang[(1)], X.A. Cao[(2)], F. Ren[(1)], S.J. Pearton[(2)], J. Han[(3)], A.G. Baca[(3)] and R.J. Shul[(3)]. [(1)]Department of Chemical Engineering, University of Florida, Gainesville, FL. [(2)]Department of Materials Science and Engineering, University of Florida, Gainesville, FL. [(3)]Sandia National Laboratories, Albuquerque NM.

We have demonstrated multiple-energy (30-325 keV) $O^+$ implantation into GaN field-effect transistor structures (n$\sim 10^{18}$ cm$^{-3}$, 3000 Å thick) to be a very viable method for device isolation. GaN based devices has shown tremendous promise for high temperature and high power applications in recent years, and performance of these devices has improved exponentially in recent years with advances in their processing. Ion implant isolation allows device processing to remain planar, as opposed to mesa etching for isolation. This eliminates problems created by step-coverage processing. Our method produced highly compensated areas for electrical isolation of devices. This directly improves device performance by reducing leakage current between devices on a common wafer. We obtained as-implanted sheet resistances of $4\text{x}10^{12}$ Ω/□. This is the best-reported sheet resistance value for ion implantation in GaN for device isolation. Our method produced thermally stable material as well. The sheet resistance remains above $10^7$ Ω/□ to annealing temperatures of $\sim$650° C. SIMS analysis was performed and no diffusion of the implanted oxygen was observed for anneals up to 800° C. Device isolation holds up well at high temperatures, where future state-of-the-art GaN devices are envisioned to operate and excel at.

**W11.69**
DEVELOPMENT OF WIDE BANDGAP SEMICONDUCTOR PHOTONIC DEVICE STRUCTRURES BY EXCIMER LASER MICROMACHINING. Qiang Zhao, Gregory W. Auner, Jie Xu, Wayne State University, Dept. of Electrical and Computer Engineering, Detroit, MI, Ratna Naik and P.K. Kuo, Wayne State University, Dept. of Physics, Detroit, MI.

AlN films were grown on Si(111), $Al_2O_3$(0001), and $Al_2O_3$(1102) substrates by plasma source molecular beam epitaxy (PSMBE.) Structural characterization of the film was performed by x-ray diffraction (XRD), reflective high energy electron diffraction (RHEED), and high resolution electron microscopy (HREM). The XRD pattern indicates complete film texture. Cross-sectional TEM reveals epitaxy of AlN on these substrates. The $Al_2O_3$(0001) and Si (111) plane is lattice matched to the c-plane growth of AlN and the $Al_2O_3$(1102) plane is lattice matched to the a-plane growth of AlN. EXCIMER laser micromachining of the AlN films into waveguide and UV sensor pixel array photonic devices. The EXCIMER laser micromachining technique resulted in clean precise machining of AlN with high aspect ratios and straight walls (isotropic structures.) The quality of the micromachined devices is related to the AlN crystalline quality, surface roughness, and crystallographic orientation. Results of AlN micromachined optical wave guide mass sensors and a pixilated UV imaging sensors structures will be presented.

**W11.70**
GaN ETCH RATE DEPENDENCE ON ION BOMBARDMENT IN AZ-400K. C.A. Carosella, Naval Research Laboratory, Washington, DC; B. Molnar, Nova Research, INC., Alexandria; S. Schiestel, George Washington University, Washington, DC.

Selective wet etching is an important technique for device manufacturing. The AZ-400K photoresist developer solution is reported to be perfectly selective for AlN over GaN [1)]. Therefore the etch-rate ratio between these two materials of different chemical compositon is very high. We were interested to find a method to change the etching rate of GaN in AZ-400K. We report in this contribution the use of ion implantation on the change of etch rate in AZ-400K. In our experiments GaN layers were grown on sapphire or SiC substrates by MOCVD or MBE techniques. Part of the GaN layers were implanted using different implantation parameters. The etching experiments were performed in AZ-400K solutions RT and 80°C. The locally damaged GaN shows high etch rates in AZ-400K. The temperature and the ion dose play a significant role and must be carefully controlled. The change of GaN etch rate seems to be related to the damage induced change in the electrical conduction. In this contribution the basic characteristics of ion bombardment introduced etching of the GaN layers, the etch rate dependence on temperature and ion dose, together with the shape of etch profile will be reported.

[1] J.R. Mileham, S.J. Pearton, C.R. Abernathy, J.D. MacKenzie, R.J. Shul and S.P. Kilcoyne, Appl. Phys. Lett. 67, p. 1119, 1995

**W11.71**
STUDY OF THE OXIDATION OF GALLIUM NITRIDE EPILAYERS IN DRY OXYGEN. P. Chen, R. Zhang, X.F. Xu, Z.Z. Chen, Y.G. Zhou, S.Y. Xie, H. Chen, S.L. Gu, B. Shen, Yi Shi and Y.D. Zheng, Department of Physics, Nanjing University, Nanjing, PR CHINA; Z.C. Huang Raytheon ITSS, Baltimore, MD; J. Hu, Syscaching Corp., Aliso Viejo, CA.

The oxidation of GaN epilayers in dry oxygen has been investigated. The GaN epilayers, about 1 $\mu$m-thick, are grown on (0001) sapphire substrates by Rapid-Thermal-Process/Low Pressure Metalorganic Chemical Vapor Deposition. The GaN epilayers are placed in dry oxygen at different temperatures for different time. The $\theta$-$2\theta$ scan X-ray diffraction (XRD) spectroscopy is used to characterize the process of oxidation. XRD data show that the oxidation of GaN began at 800°C for 6 h. When the GaN are oxidized at higher temperatures or longer time, notable oxidation can be observed from XRD data. The oxide is identified as the monoclinic $\beta$-$Ga_2O_3$. The GaN diffraction peaks disappear at 1050°C for 4 h or at 1100°C for 1 h, which indicates that the GaN epilayers has been completely oxidized under these conditions. For all samples, the strongest oxides peak is (11-3), which is followed by (30-6). For investigating the oxidation kinetics, the measured intensity of the $\beta$-$Ga_2O_3$ (11-3) XRD peak is studied as a function of oxidation time at various temperatures. It is found that the oxidation is limited by the rate of an interfacial reaction at 900°C-1000°C, and controlled by the diffusion mechanism at higher temperatures. When the temperature reaches 1100°C, the oxidation rate is very fast, which is considered as the results of the GaN decomposition at high temperature under atmosphere.

**W11.72**
ANNEALING OF ION IMPLANTATION DAMAGE STUDIED BY PHOTOLUMINESCENCE. N.K. Langford, J.S. Williams, C. Jagadish, Department of Electronic Materials Engineering, Research School of Physical Sciences & Engineering, The Institute of Advanced Studies, The Australian National University, Canberra, AUSTRALIA; and S.J. Pearton, Dept of Materials Science Engineering, University of Florida, Gainesville, FL.

Ion implantation is an important selective doping technique for both active layer and contacts in high power electronic devices based on GaN. However, ion implantation unavoidably generates damage to GaN which is impossible to remove completely at annealing temperatures $<$ 1000 °C. Annealing at higher temperatures is extremely difficult and only partially successful to date due to severe surface dissociation. As a result, optimum electrical activation is a challenge in GaN, requiring innovative methods to remove implantation damage. In this paper ion implantation damage is characterised by photoluminescence (PL), as a function of annealing temperature, using excitation wavelengths from 200 to 600 nm. Implantation os hydrogen is chosen for most detailed study since such a light species introduces dilute, discrete damage, ideal for PL. However Si-implanted GaN has also been studied. Results show that implantation results in a degradation of band-edge luminescence with increasing ion dose. Recovery occurs progressively during annealing. For H-implantation at doses $<$ $10^{16}$ cm$^{-2}$, full recovery occurs by 1000°C but for Si implantation higher temperatures are required to fully recover PL. This behaviour correlates well with previously measured electrical measurements for Si-implanted GaN. Changes in other luminescent centres present in the starting GaN material are

also observed by PL after implantation and all such emissions recover to the levels in the starting material on annealing. Surprisingly, no new optically luminescent peaks are introduced into the GaN band gap by ion implantation.

**W11.73**
A NEAR DAMAGE FREE ETCHING PROCESS IN GaN.
J.M. Hwang, J.T. Hsieh, H.L. Hwang, National Tsing-Hua Univ, Dept of Electrical Engineering, Hsin-Chu, Taiwan, R.O.C; W.H. Hung, Synchrotron Radiation Research Center, Hsin-Chu, Taiwan, R.O.C.

Photoluminescence (PL) was used to study the surface damage produced by photoelectrochemical (PEC) etching GaN with KOH electrolyte. In the etching process, OH- prefer to take away gallium atom than nitrogen, so a thin damage layer with complex defect of Ga vacancy bond oxygen in nitrogen site was formed. The surface defect create a broaden yellow luminescence (YL) peak centered at 2.2eV in room temperature PL spectrum. The temperature dependent properties of etching induced yellow luminescence was discussed. For removing the etching damage, we used a boiled KOH solution to remove the thin damage layer. The boiled KOH treatment have crystallography etching stop at (0001) and {10-10} face. From the SEM and PL after the boiled KOH solution treatment, a smooth etching surface, mirror like side wall and comparable PL with as-growth GaN was found. The composition of PEC etching with and without post-treatment by the boiled KOH was also studied by auger electron spectron (AES) depth profile. The etching surface have similar composition with as-growth surface. A near damage free etching process evidenced by YL reduction and AES were revealed in this paper.

**W11.74**
FABRICATION AND CHARACTERIZATION OF InGaN NANO-SCALE DOTS FOR BLUE AND GREEN LED APPLICATIONS.
K.S. Kim, C.-H. Hong, C.S. Oh, W.-H. Lee, K.J. Lee, O.H. Cha, C.S. Kim, G.M. Yang, E.-K. Suh, K.Y. Lim, and H.J. Lee, Dept. of Semiconductor Science and Technology, Semiconductor Physics Research Center, Chonbuk National University, SOUTH KOREA.

InGaN nano-scale dots, which are considered as a mixture of quantum dot and quantum disk, were grown on GaN barrier using low-pressure metalorganic chemical vapor deposition. The structural and optical properties of InGaN dots have been characterized by atomic force microscopy (AFM), temperature dependent photoluminescence (PL), and high-resolution X-ray diffraction measurements. AFM studies indicate that InGaN dots, with the diameter of 10∼60 nm and the height of 6∼8 nm are randomly formed on InGaN surface and the average dot density is about $4\times10^{9}$ $cm^{-2}$. For that case with 30 nm-thick GaN capping layer, the surface morphology is wavy and some terraces are visible. The rms roughness is as low as 2.1 nm. The thermo-activation energy of InGaN dots is approximately 51 meV based on the analysis of the integrated PL intensity. The PL transition energies in InGaN nano-scale dots were well fitted as a function of temperature. We found that the nano-scale dots due to spatially strong compositional fluctuation play an important role in the phase separation properties of InGaN quantum well emission. Also blue and green LEDs were successfully fabricated by applying high quality InGaN dots. The I-V characteristics of the fabricated LEDs showed operating voltage is 3∼3.5 V.

**W11.75**
ELECTRICAL PROPERTIES AND MICROSTRUCTURE OF Ti BASED OHMIC CONTACTS TO GaN.
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Conventional ohmic contacts on type GaN are obtained by depositing Ti and Al thin layers (total thickness ∼ 100-200 nm) followed by a high temperature alloying anneal. The ohmic contact has been shown to be due to a thin TiN film from the reaction of Ti with GaN. In this process, resistance in the range of $10^{-5}$ ohm.$cm^{-2}$ is obtained upon $10^{-18}$ $cm^{-2}$ silicon doped GaN layers. During the annealing steps many reactive phases form between Al, Ga, Ti and N which may be a problem for the quality of the contact. Moreover the formation of TiN may lead to a loss of N from the GaN surface layer, as well as to an excess of Ga in to reactive area. We have carried out TEM investigations on annealed Al/Ti/GaN and directly deposited TiN films. In the Al/Ti/GaN system, the annealing step gave rise to a ∼ 20 nm rough TiN film. The ohmic contact is made by TiN crystallites which are epitaxially related to GaN which (0001)GaN‖(111) TiN, in between, amorphous patches of 1 to 2 nm extension can be found. When the stoechiometric TiN was deposited directly on GaN, we obtained columnar TiN grains of 10-20 nm section which cross the whole film thickness and are rotated mostly around the [111] axis. The same epitaxial relationship is obtained and no amorphous patches are observed at the interface. Depending on the GaN layer morphology, the (111) atomic planes of TiN can be slightly tilted in order to accommodate the misorientation. Electrical measurements show that the ohmic contact is obtained upon TiN deposition even at room temperature and its quality is improved with additional annealing.

**W11.76**
HIGHLY CHEMICAL REACTIVE ION ETCHING OF GALLIUM NITRIDE AND ITS INFLUENCE ON SCHOTTKY CONTACTS.
Fouad Karouta, Bart Jacobs, Eindhoven Univ of Technology, Faculty of Electrical Engineering, Div TTE, NETHERLANDS; Ingrid Moerman, Koen Jacobs, INTEC, Univ of Ghent, BELGIUM; Jan Weyher, Sylvester Porowski, High Pressure Research Center, Polish Academy of Sciences, Warsaw, POLAND; Rachel Crane, Paul Hageman, Katholieke Univ Nijmegen, RIM, NETHERLANDS.

Reactive ion etching is known to induce damages in semiconductor structures mainly due to the physical sputtering. This undesired damage can be avoided in GaAs and InP based transistors by using wet chemical etching. This is not valid for GaN based structures as dry etching technique is required for processing electronic devices. In this work we present a novel chemistry for RIE of GaN based on $SiCl_4$:Ar:$SF_6$. This gas combination allows high etching rate at relatively low DC bias. For instance, at an RF power of 105 W, an etch rate of 95-100 nm/min can be achieved resulting in a very smooth surface (DC bias of -300 V). Assuming that the physical sputtering is due to Ar, the chemical component of this RIE process is estimated to be 90%. In the perspective of using GaN substrates for homo-epitaxy of high quality GaN/AlGaN structures, we have used the above described RIE process to smoothen Ga-polar GaN substrates. The RMS value, measured by AFM, went from 2 nm (after mechanical polishing) down to 0.4 nm after 6 minutes of RIE. Etching N-polar GaN resulted in a higher etch rate than Ga-polar materials (165 vs. 110 nm/min). Heat treatment of etched surfaces has revealed the possibility of a good recovery of the electrical properties of the GaN layer. The influence of the RIE process was investigated on Schottky contacts. Those were made on as-grown GaN ($2x10^{17}$ $cm^{-2}$) and also on the same material after a short RIE process followed by a HCl dip and a heat treatment at 600°C. The reverse current and the ideality factor were found to be respectively $4x10^{-4}$ A/mm (-20V), 1.12 (as-grown) and $1x10^{-3}$ A/mm, 1.12 (after RIE, etc.). Based on these results we claim the feasibility of gate-recessed AlGaN HEMTs.

**W11.77**
IMPROVED LOW RESISTANCE CONTACTS OF Ni/Au AND Pd/Au TO p-TYPE GaN USING A CRYOGENIC TREATMENT.
Mi-Ran Park, Wayne A. Anderson, State University of New York at Buffalo, Dept of Electrical Engineering, Amherst, NY; Seong-Ju Park, Kwangju Institute of Science and Technology, Dept of Materials Science and Engineering, Kwangju, KOREA.

A low resistance Ohmic contact to p-type GaN is essential for reliable operation of electronic and optoelectronic devices. Such contacts have been made using Ni/Au and Pd/Au contacts to p-type Mg-doped GaN ( $3x10^{17}$ $cm^{-3}$ ) grown by metal organic chemical vapor deposition (MOCVD) on (0001) sapphire substrates. Thermal evaporation was used for the deposition of those metals followed by annealing at temperatures of 400∼700 °C in a nitrogen gas ambient and an oxygen and nitrogen mixed gas ambient, then subsequently cooled in liquid $N_2$ which reduced the specific contact resistance from the range of 9.46 ∼ $2.80x10^{-2}$ Ωcm$^2$ to $2.69x10^{-4}$ Ωcm$^2$ for Ni/Au and from the range of 8.35 ∼ $5.01x10^{-4}$ Ωcm$^2$ to 4 ∼ $2x10^{-4}$ Ωcm$^2$ for Pd/Au. The electrical characteristics for the contacts were examined by the current versus voltage curves and the specific contact resistance was determined by use of the circular transmission line method (c-TLM). The current transport mechanisms have also been studied by the current versus voltage measurements at elevated temperatures (I-V-T). The effects of the cryogenic process on improving Ohmic behavior ( I-V linearity ) and reducing the specific contact resistance will be discussed from a microstructural analysis which reveals the metallurgy of Ohmic contact formation.

**W11.78**
A THERMODYNAMIC APPROACH TO OHMIC CONTACT FORMATION: APPLICATION TO P TYPE GALLIUM NITRIDE.
B. Liu, M.H. Ahonen, P.H. Holloway, Univ of Florida, Dept of Materials Science and Engineering, Gainesville, FL.

One approach used to form ohmic contacts to compound semiconductors has been the formation of stable metal compounds to one semiconductor component. In the current research, this has been extended to the "NOG" (Nitride-forming-metal Over

Gallide-forming-metal) scheme for p-GaN, which utilizes the fact that metals could be classified according to the enthalpy of compound formation into gallide-forming, nitride-forming or neutral groups. The potential of the "NOG" scheme was evaluated for Ni/Ti/Au and Ni/Al/Au metallization where Ti and Al are nitride forming metals and Ni is a gallide forming metal. The results were compared with those of Ni/Au contacts. Under the same conditions, smaller contact resistance could be obtained with these new schemes, although the contacts were still highly resistive. Also Ti was shown to be better than Al as the nitride-forming metal based on the decrease of contact resistance. Compared to Ni/Au, four times more current was measured in Ni/Ti/Au contact to p-GaN after an anneal at 300°C for 5 min. Published ohmic contact schemes to p-GaN have also been evaluated and the concept of "NOG" was shown to be successful in understanding these contact schemes. Potential problems of the "NOG" contact scheme will also be discussed.

**W11.79**
METAL/NITRIDE CONTACTS STUDIED BY ELECTRON SPECTROSCOPIES. J. Dumont, R. Sporken, Univ. of Namur, Laboratoire LISE, Namur, BELGIUM; E. Monroy, E. Muñoz, Universidad Politecnica de Madrid, E.S.T.I., Ciudad Universitaria, Madrid, SPAIN.

Metal/n-GaN and metal/n-AlGaN (metal = Au, Pt, Pd, Ni, Ti) have been studied by photoelectron spectroscopy (XPS, UPS) and Auger electron spectroscopy. Both depth profiling with argon ion sputtering and in situ interface formation studies were done. Two methods were used to prepare clean GaN surfaces. Method 1 consists in wet chemical etching followed by heating in UHV. This leaves some O contamination and, in some cases, some C contamination on the surface. In method 2, the samples were first exposed to atomic hydrogen at high temperature. A layer of Ga was then deposited. After thermally desorbing the Ga layer, XPS and Auger spectra are characteristic of stoichiometric surfaces without detectable O and C contamination. Ti/GaN interfaces are found to be reactive, whereas the four other metals form sharp interfaces. The influence of argon ion bombardment was studied in detail in the case of Au contacts. It is shown that ion bombardment induces the formation of an interfacial layer containing Au and Ga. Moreover, a small amount of Ga is detected in the Au layers deposited on samples cleaned according to method 1. This Ga in the Au layer is detected too far from the interface to be due to the ion bombardment. Finally, the Schottky barrier height was measured and was found to be determined mostly by the metal work function.

**W11.80**
PHOTOCAPACITANCE STUDY OF DEEP LEVELS IN MOCVD-GROWN N-GaN. Adrian Hierro, Daewon Kwon, Steven A. Ringel, The Ohio State University, Dept. of Electrical Engineering, Columbus, OH; Monica Hansen, James S. Speck, Steven P. DenBaars, Materials and Electrical and Computer Engineering Departments, University of California Santa Barbara, CA.

Deep levels throughout the entire bandgap of n-type GaN are investigated by means of Deep Level Optical Spectroscopy (DLOS) based on photocapacitance transient analysis. The GaN samples were grown in a horizontal MOCVD reactor on c-plane sapphire. An unintentionally doped 1.35 $\mu$m-thick n-type layer (n$\sim$6$\times$10$^{16}$ cm$^{-3}$) with a threading dislocation density of $\sim$10$^{9}$ cm$^{-2}$ was grown on heavily Si-doped n-type buffer layers, followed by a 1500 Å-thick Mg-doped p$^{+}$ GaN cap layer. Front semitransparent (80 Å-thick) Pd/Au ohmic contacts were fabricated to allow the DLOS measurements. Back ohmic contacts were obtained by depositing 1 $\mu$m-thick Ti/Al/Ni/Au films. The diode size was 0.23 mm$^2$, and excellent rectifying behavior was obtained with a turn-on voltage of $\sim$2.2 V and a leakage current below 6.5$\times$10$^{-9}$ A/cm$^2$ at the DLOS conditions. The DLOS experiments were performed at 300 K under a reverse bias of -1 V using Xe and quartz-halogen lamps as light sources. Several deep levels are observed at 1.0, 1.5, 2.6, 3.04 and 3.22 eV from the conduction band with concentrations in the 10$^{14}$ cm$^{-3}$ range. The 3.04 and 3.22 eV levels are believed to be related to background Mg, whereas the 2.6 eV level may be related to the yellow band in GaN. Depth profiling DLOS indicates an increase in the 1.5 and 2.6 eV level concentrations as the p-n junction is approached. Spatial variations in the concentration of the 1.5, 2.6 and 3.04 eV levels across the sample were detected, and are likely related to gas flow depletion in the horizontal reactor during growth. Detailed comparisons between the DLOS spectra as a function of growth parameters such as dopant type and concentration, as well as flow conditions will be made so that potential sources for the deep levels can be identified.

**W11.81**
DEEP CENTERS AND PERSISTENT PHOTOCONDUCTIVITY STUDIES IN VARIOUSLY GROWN GaN FILMS. A.Y. Polyakov, N.B. Smirnov, A.V. Govorkov, Institute of Rare Metals, Moscow, RUSSIA; A.S. Usikov, N.M. Shmidt, B.V. Pushnyi, D.V. Tsvetkov, S.I. Stepanov, A.F. Ioffe Physiko-Technical Institute RAS, St.-Petersburg, RUSSIA; V.A. Dmitriev, TDI., Inc., Gaithersburg, MD.

A set of undoped and lightly Si doped GaN films was grown by MOCVD on sapphire using AlGaN and GaN low-temperature buffers and by HVPE on sapphire. Deep levels spectra were measured using DLTS and admittance spectroscopy. The films were also characterized by HRXRD, MCL spectra measurements, MCL and EBIC imaging. Diffusion lengths of minority carriers were measured from EBIC profiles. Deep levels spectra of AlGaN-buffered and HVPE-grown films, as detected by DLTS and admittance spectroscopy, were quite simlar. The most prominent centers were electron traps with apparent activation energies of 0.6 eV and 0.8 eV. The density of all electron traps was very much lower in GaN-buffered MOCVD-grown films. This, however, had virtually no effect on the measured values of diffusion lengths which were always even higher for the samples with high trap density. This was further confirmed by the fact that the diffusion length values could be varied in a wide range (from 0.4 microns to 2 microns) for AlGaN-buffered films without any obvious changes occurring to the density of DLTS traps. Persistent photocapacitance measurements on various samples show that although qualitatively the effects are quite similar in high-traps-density and low-traps density films there are certain features that distinguish one class of samples from the other. Possible roles of deeper traps not detectable by DLTS and of potential fluctuations in the samples will be discussed.

**W11.82**
FERMI LEVEL PINNING AT GaN-INTERFACES: CORRELATION OF ELECTRICAL ADMITTANCE AND TRANSIENT SPECTROSCOPY. H. Witte[1], A. Krtschil[1], M. Lisker[1], D. Rudloff[1], J. Christen[1], A. Krost[1], M. Stutzmann[2]; [1]Institute of Experimental Physics, Otto-von-Guericke-University Magdeburg, Magdeburg, GERMANY; [2]Walter Schottky Institute, Technical University Munich, Garching, GERMANY.

Deep defect levels were characterized in gallium nitride layers grown by molecular beam epi-taxy (MBE) and by metalorganic vapor phase epitaxy (MOVPE) using thermal admittance spectroscopy (TAS) (20Hz - 1MHz) and low frequency deep level transient spectrocopy (LF-DLTS, with modulation frequencies of 10kHz - 100kHz). Pt-Schottky contacts and annealed Al- Ohmic contacts were used. Depending on surface roughness as determined by atomic force microscopy the Schottky barriers break down at decreasingly low frequencies. LF-DLTS electron traps with thermal activation energies of 0.17eV, (0.2-0.26)eV, and 0.62eV were identified which are well known from the literature. In contrary to these LF-DLTS results, probing the whole depth of the space charge region, only one defect state is found in each sample using TAS. High emission rates are measured for these electron traps and the activation energies are (130-180) meV and (200-260) meV, respectively. This effect can be only explained by a pinning of the Fermi level at the corresponding defect induced by a high densities of surface states. The TAS measurements are performed at zero voltage and the signal results from recharging effects near the Fermi level. Therefore, TAS is highly sensitive for both, surface defects as well as the behaviour of the Fermi level in contrast to the non-equilibrium recharging process used in the DLTS spectra. This interpretation is supported by reference measurements on Te-doped GaAs samples which in contrast show no Fermi level pinning and all there experimental techniques (DLTS, LF-DLTS, and TAS) give identical results.

**W11.83**
PHOTOCURRENT SPECTROSCOPY INVESIGATIONS OF Mg-RELATED DEFECT LEVELS IN P-TYPE GaN. S.J. Chung, O.H. Cha, H.K. Cho, M.S. Jeong, C.-H. Hong, E.-K. Suh and H.J. Lee, Semiconductor Physics Research Center and Department of Semiconductor Science and Technology, Chonbuk National University, KOREA.

The defect levels associated with Mg doping concentration in p-type GaN films were systematically investigated by photocurrent (PC) spectroscopy. Mg-doped GaN samples grown by metal organic chemical vapor deposition on sapphire substrate were thermally annealed in nitrogen atmosphere at 850°C for 10 minutes. At room temperature, typical broad PC spectra showed two peaks at 3.31 and 3.15 eV associated with acceptor levels formed at 300 and 140 meV above valence band in as grown samples. But, in thermal annealed samples, PC spectra exhibited various additional peaks depending on the Mg concentration. For the heavily Mg doped GaN samples 6$\sim$7$\times$10$^{17}$ cm$^{-3}$, we have observed PC peaks related to Mg at 3.31 and 3.02 eV and carbon acceptor at 3.17 eV. For moderately Mg doped GaN samples 3$\sim$4$\times$10$^{17}$ cm$^{-3}$, additional peak on the low energy side was observed at around 0.9 eV. This peak is may be related to the Ga vacancy located at around 900 meV above valence

band, but the origin is not clearly understood as yet. But, for relatively low Mg doped samples which hole concentration is $1\sim2\times10^{17}$ $cm^{-3}$, additional broad peak was observed at around 1.2 eV. This peak may be related to the yellow band luminescence from defects. We believe that the yellow band luminescence is strongly related to Ga vacancy. As the Mg concentration is increased, Ga vacancies can be reduced because Mg occupies the substitutional site of Ga in the GaN lattice. When hole concentration is above $6\sim7\times10^{17}$ $cm^{-3}$, the yellow luminescence and Ga vacancy related peaks were completely disappeared. On the other hand, the PC peak intensities related to Mg acceptor levels were increased with increasing Mg concentration.

**W11.84**

CHARACTERISTICS OF DEEP CENTERS IN N-GaN GROWN BY REACTIVE MOLECULAR BEAM EPITAXY. Z-Q. Fang, D.C. Look, Wright State University, Semiconductor Research Center, Dayton, OH; W. Kim, LG Corporate Institute of Technology, Seoul, KOREA; H. Morkoc, Virginia Commonwealth University, Dept of Electrical Engineering, Richmond, VA.

Deep centers in Si-doped n-GaN samples grown on sapphire by reactive molecular beam epitaxy (RMBE), using different ammonia flow rates (AFR), have been studied by deep level transient spectroscopy (DLTS) over a temperature range 80 to 400 K. In addition to the DLTS centers A, B, C, and D at 0.67 eV, 0.62 eV, 0.45 eV and 0.24 eV, respectively, below the conduction band, which were previously reported in n-GaN layers grown by both metalorganic chemical-vapor deposition (MOCVD) and hydride vapor-phase epitaxy (HVPE), three new centers, labelled as $A_1$, $C_1$, and $E_1$, have been observed. $A_1$, with an activation energy of 0.89 eV and concentrations of mid-$10^{15}$ to low-$10^{16}$ $cm^{-3}$, is a dominant center in RMBE-GaN layers. $C_1$, with a low-field activation energy of 0.44 to 0.49 eV (depending on carrier concentration), is also a prominent center in the layers and shows a strong electric field effect: both the peak position and the peak height are affected by the applied bias. On the other hand, $E_1$, with an activation energy of 0.25 eV and an apparent cross section of 3 x $10^{-13}$ $cm^2$, shows a close connection with the AFR; i.e. $E_1$ cab be clearly observed only at a low AFR. Based on a comparison between traps $E_1$ and E (the latter was observed in n-GaN layers, grown by both MOCVD and HVPE, after 1-MeV electron-irradiation), we believe that $E_1$ is a defect complex involving the nitrogen vacancy.

**W11.85**

SOME STUDIES ON THE HYDROGEN INCORPORATION IN GaN GROWN BY METALORGANIC CHEMICAL VAPOR DEPOSITION. Chengxin Wang, Xianglin Liu, Xiaohui Wang, Peide Han, Du Wang, and Dacheng Lu.

We studied the hydrogen incorporation in undoped, Si-doped and Mg-doped GaN grown by an reduced pressure metalorganic chemical vapor deposition (MOCVD). Using nuclear reaction analysis(NRA) $^{19}F(^1H,\alpha\gamma)^{16}$% O at the energy of 6.418MeV, we found that no hydrogen was detected above the measurement limit of NRA ($\sim10^{17}cm^{-3}$) for each as-grown and annealed n-type GaN sample, our results demonstrated that the diffusion barrier for hydrogen in n-GaN was very high, and approved the theoretical conclusion. However, there was a large number of hydrogen in as-grown Mg-doped GaN, but it disappeared after thermal annealing in $N_2$ ambient at 750°C for 30min. After annealed the p-type GaN in $NH_3$ atmosphere at 750% °C for 30 min, a significant incorporation of hydrogen appeared in GaN epilayer again. In as-grown Mg-doped GaN, NRA profile shown that the hydrogen concentration were very smooth with a concentration of $\sim2\% \times 10^{21}cm^{-3}$ in the whole epilayer, for p-type GaN annealed in NH% $_3$, the hydrogen concentration of $\sim1\times10^{21}cm^{-3}$ below the surface with a slowly varying monatomic decrease to a value of $5\times10^{20}cm^{-3}$ at a depth of $\sim1\mu$m. From the SIMS results, the Mg concentration in Mg-doped GaN was about $4\times10^{19}cm^{-3}$, so the amount of hydrogen in as-grown Mg-doped GaN and p-GaN annealed at $NH_3$ were much larger than that of Mg atoms in GaN, not as shown, by the theoretical calculation, that the H concentration essentially equals the Mg concentration when H is present. It seems that there are other significantly complex processes in the hydrogen incorporation in Mg-doped GaN, maybe in addition to Mg-N-H, large number of other complex or interstitial H exist in Mg-doped. It approved some recent theoretical results from the first principle calculations.

**W11.86**

DEEP LEVELS STUDIES IN AlGaN-BASED LED STRUCTURES. A.Y. Polyakov, N.B. Smirnov, A.V. Govorkov, M.G. Mil'vidskii, Institute of Rare Metals, Moscow, RUSSIA; A.S. Usikov, B.V. Pushnyi, W.V. Lundin, A.F. Ioffe Fisiko-Technical Institute RAS, St.-Petersburg, RUSSIA.

Deep centers were studied in GaN homojunction, AlGaN heterojunction and AlGaN/GaN/AlGaN double heterojunction LED p-i-n structures prepared by MOCVD on sapphire. The effects of i-GaN active layer growth at reduced temperatures and of doping this layer with Zn or Zn and Si were looked into. The structures were investigated by means of I-V, C-V, electroluminescence (EL) spectra, DLTS and admittance spectroscopy measurements. It is shown that the i-GaN layers in homojunction structures are most probably converted to p-type due to Mg in-diffusion from the p-GaN layer. Growing the p-AlGaN layer with Al composition of about x=0.05-0.07 strongly suppresses such in-diffusion and allows to shift the main band of the EL spectra to shorter wavelength. Zn or Zn+Si doping of the middle portion of the active i-GaN layer produced a new band near 2.9 eV (Zn) or near 2.7 and 2 eV (Zn+Si). Growth of the i-layer at reduced temperatures resulted in strong yellow luminescence becoming dominant in EL spectra. The dominant centers detected in i-GaN layers were the electron traps with apparent ionization energies of 0.55 eV and 0.85 eV. The latter trap was not observed in Zn or Zn+Si doped samples. The main hole traps detected in p-GaN films of the structure were the traps with apparent activation energies of 0.16 eV (Mg acceptors), 0.4 eV and 0.9 eV. The 0.4 eV hole traps seem to be responsible for the blue luminescence of the Mg doped films and for persistent photoconductivity observed in such layers.

**W11.87**

NEGATIVE-U PROPERTIES OF A METALLISATION INDUCED ELECTRON TRAP IN EPITAXIALlY GROWN n-GaN. W.E. Meyer, F.D. Auret, S.A. Goodman, University of Pretoria, Dept of Physics, Pretoria, SOUTH AFRICA; F.K. Koschnick, J.-M. Spaeth, Universität GH Paderborn, Fachbereich Physik, Paderborn, GERMANY; B. Beaumont, P. Gibart, CRHEA-CNRS Valbonne, FRANCE.

We have used deep level transient spectroscopy (DLTS) to investigate the electrical properties of two defects introduced in n-GaAs after Sputter deposition of Au Schottky contacts. The two defects, ES1 and ES2, located at $E_C$ - 0.22 ± 0.02 eV and $E_C$ - 0.30 ± 0.01 eV, respectively and exhibit metastable-like behaviour. Both defects can be removed under a zero bias at temperatures of as low as 20 K and are re-introduced during reverse bias annealing at temperatures of 100 K - 125 K and 115 K - 140 K, respectively. The electric field enhanced emission from these defects indicate that the defects can exist in three charge states: as a positively charged donor, a neutral state as well as a negatively charged acceptor. We show that the metastability of the defect can be explained by its negative-U properties (i.e. capture of a second electron releases more energy than the capture of the first).

## SESSION W12: QUANTUM DOTS, OPTICAL CHARACTERIZATION, RARE EARTHS

Chair: Brian J. Skromme
Friday Morning, December 3, 1999
Room 302 (H)

**8:30 AM *W12.1**

GROWTH OF InGaN/GaN NANOSTRUCTURES FOR VCSELS AND QUANTUM DOT LASERS. Yasuhiko Arakawa and Takao Someya, Research Center for Advanced Science and Technology, Institute of Industrial Science, University of Tokyo, Tokyo, JAPAN.

We discuss our recent progress on growth, optical characterization, and device demonstration for nitride-based vertical cavity surface emitting lasers (VCSELs) and quantum dot (QD) lasers. After brief discussion on impact of nanostructures on nitride-based optical devices, we first present growth and processing of post-type nitride-VCSELs. A nitride DBR consisting of 43 pairs of GaN layers and $Al_{0.34}Ga_{0.82}N$ layers were grown on a (0001) sapphire substrate by atmospheric-pressure MOCVD. Then, a 2.5$\lambda$ cavity comprising 26 periods of $In_{0.1}Ga_{0.9}N$ quantum well layers was grown on the nitride DBR. Finally, a reflector consisting of 15 periods of $ZrO_2/SiO_2$ multi-layer (oxide DBR) was evaporated on the top of the GaN-based multi-layer to form a vertical cavity. The reflectivities of the nitride and oxide DBRs were 98% and 99.5%, respectively. We achieved the first room-temperature demonstration of lasing action at 399 nm in optically-pumped VCSELs. We will also discuss self-assembling growth of InGaN QDs on GaN epitaxial layer. The density of the QD was up to $1.2x10^{10}cm^{-2}$ with the minimal diameter of 9 nm. Extremely sharp luminescence lines from individual localized states of the QD structures were observed by micro-photoluminescence measurement . The successful growth of stacked QD structures (10-layers) led to the first lasing action in InGaN QD lasers at room temperature by optical pumping.

**9:00 AM W12.2**

CONTROL OF FORMATION SITES OF SELF-ASSEMBLING GaN DOTS BY FOCUSED ELECTRON BEAM EXPOSURE. Koji Kawasaki[1,2,3], Daisuke Yamazaki[1], Kazuo Tsutsui[1,3] and Yoshinobu Aoyagi[1,2,3] Tokyo Inst of Tech[1], Interdisciplinary Grad

Sch of Sci and Eng, Yokohama, JAPAN; RIKEN[2], Wako, JAPAN; CREST of JST[3], Wako, JAPAN.

For realization of the quantum logic gates such as 'qubit' or 'controlled not' using the coupled quantum dots, the control of the size and the distance between the quantum dots are required. Well-controlled coupled GaN quantum dots are good candidate for the realization because of rather unsensitive nature of the dots to the surface state. We have succeeded in quantum dot formation of GaN with a nanometer scale using the droplet epitaxy technique and the formation site of GaN dots is successfully controlled by a focused electron beam. After chemical treatments of a 6H-SiC (0001) substrate, the surface was directly exposed to a focused electron beam with dot matrix pattern at RT in the electron beam exposure apparatus. Then, the exposed sample was cleaned by ozone ambience and loaded to the molecular beam epitaxy system. After thermal cleaning at 600°C for 10 min, Ga droplets were formed at 600°C and then, $NH_3$ gas was supplied and the sample was annealed at 800°C for 10 min. It was found that GaN dots of which diameter was less than 40 nm were obtained by this growth technique from the results of the PL measurement and the high-resolution SEM observation. In addition, a GaN dot was formed at the electron-beam-exposed center while nucleations of the dots were suppressed around the exposed center. This result means that the position of GaN quantum dots formed by self-assembling technique can be controlled by electron beam exposure. The mechanism of the control of the formation sites will be discussed in detail at the presentation.

**9:15 AM W12.3**
FOCUSED ION BEAM ETCHING OF NANOMETER-SIZE GaN/AlGaN DEVICE STRUCTURES AND THEIR OPTICAL CHARACTERIZATION BY MICRO-PHOTOLUMINESCENCE/ RAMAN MAPPING. M. Kuball, M. Benyoucef, H.H. Wills Physics Laboratory, University of Bristol, Bristol, UNITED KINGDOM; F.H. Morrissey, Philips Electron Optics BV, Eindhoven, NETHERLANDS; C.T. Foxon, Department of Physics, University of Nottingham, Nottingham, UNITED KINGDOM.

We report on the nano-fabrication of GaN/AlGaN device structures into pillars as small as 20nm to 500nm in diameter by focused ion beam (FIB) etching and their evaluation by micro-photoluminescence/Raman mapping, illustrated on a GaN/AlGaN heterostructure field effect transistor (HFET). The results demonstrate the great potential of focused ion beam (FIB) etching for the fabrication of ultra-small electronic and opto-electronic devices. Reactive ion etching and wet etching techniques have mostly been employed for the fabrication of nitride based devices; these, however, are not the preferred techniques for the nano-fabrication of GaN-based devices. Focused ion beam (FIB) etching is one of the most promising techniques for the fine patterning of GaN, however, only basic etching parameters have been investigated so far. GaN/$Al_{0.15}Ga_{0.85}N$ HFET device structures were micro-machined using a FEI 2000 focused ion beam system. Gallium ion beam currents as low as 1pA were used to fabricate pillars as small as 20nm in diameter from the HFET structures. Micro-photoluminescence and UV micro-Raman maps were recorded from the FIB etched pattern using a Renishaw ultraviolet (UV) Micro-Raman system. Photoluminescence was detected from the nanometer-size GaN/$Al_{0.15}Ga_{0.85}N$ HFET structures, i.e., from the $Al_{0.15}Ga_{0.85}N$ as well as the GaN layers in the device structure, despite the induced etch damage. The spatial distribution of GaN and AlGaN in the FIB-etched areas was mapped using UV Micro-Raman spectroscopy. Damage introduced by FIB-etching was characterized. The fabricated nanometer-size nitride structures were found to be of reasonable good quality, even without post-processing steps to reduce etch damage.

**9:30 AM *W12.4**
SPECTROSCOPY IN POLARIZED AND PIEZOELECTRIC AlGaInN HETEROSTRUCTURES. Christian Wetzel, High Tech Research Center, Meijo University, Nagoya, JAPAN; Hiroshi Amano and Isamu Akasaki, High Tech Research Center and Department of Electrical and Electronic Engineering, Meijo University, Nagoya, JAPAN.

Uniaxial wurtzite group-III nitride heterostructures are subject to very large polarization effects with significant consequences for fundamental physics as well as for optoelectronic and transport device applications. A central aspect for the proper implementation of these effects is the experimental quantification of polarization charges and associated fields. In modulated reflection spectroscopy of thin films and heterostructures of GaInN, GaN, and AlGaN we observe pronounced Franz-Keldysh oscillations that allow direct and accurate readings of the field strength. In GaInN/GaN heterostructures, we identify a clear correlation of electric field with interband transitions in absorption as well as in the emission. Beyond the well-known case of field dependent level shifts, we observe the field dependent splitting of the respective levels. Unlike in other systems, this observation is not limited to superlattice structures. Reported discrepancies of absorption and emission edges are found as a relaxation process between discrete levels rather than a random localization process. Those levels together with the energy of stimulated emission and the bulk band gap energy vary in a very regular pattern to each other. We combine results of samples with variable composition, well width, and perturbations under external fields to develop a concept of a polarization controlled electronic bandstructure. Our model satisfactorily accounts for various observations in the literature and provides a basis for further optimization schemes. This work was partly supported by the JSPS and MESSCJ.

**10:30 AM W12.5**
EVIDENCE FOR SPONTANEOUS POLARIZATION EFFECTS IN GaN/AlGaN QUANTUM WELLS. J. Simon, R. Langer, A. Barski, N.T. Pelekanos, Departement de Recherche Fondamentale sur la Matiere Condensee, CEA/Grenoble, Grenoble, FRANCE.

In wurtzite c-axis-grown nitride heterostructures, in addition to piezoelectric effects, one expects at least as intense spontaneous polarization (SP) effects, both generating large electric fields. Even though several groups have reported the observation of such fields, still, it has not been established experimentally whether SP effects played indeed a role in nitride heterostructures. In this report we describe optical work on different GaN/AlGaN quantum well (QW) samples with aluminium concentration $X_{Al}$ varying from 7 to 24%. The samples are grown by molecular beam epitaxy and they typically consist of 20, 40 and 60$\AA$-thick single QWs separated by 100$\AA$ AlGaN barriers. X-ray diffraction experiments allowed to measure directly on each sample $X_{Al}$ and confirm that all samples remained pseudomorphic on the substrate. In T=2K photoluminescence (PL) experiments, we observed strong PL redshifts of the QW emission with increasing QW thickness and with respect to the GaN gap. This is a clear manifestation of a giant electric field F present in the QW. We measured F for all samples by fitting the experimental $e_1h_1$ transition energies using F as parameter. In this calculation a realistic band profile taking into account electric-field-induced band-bending has been used. Considering that $F=(\Delta P/\epsilon\epsilon_0)\cdot L_B/(L_W+L_B)$, where $L_W$ ($L_B$) is the total QW (barrier) thickness, and $\Delta P$ is the difference of the total polarization between QW and barrier layers, we determined $\Delta P$ in each sample and verified that it depends linearly on $X_{Al}$. Furthermore, we compared $\Delta P$ with the piezoelectric polarization difference $\Delta P_{PZ}$, estimated using available piezoelectric coefficients, and found that for all samples $\Delta P/\Delta P_{PZ}$ is significantly over 1. This clearly suggests a non-piezoelectric contribution to $\Delta P$, which we interpret as direct evidence of SP effects in GaN/AlGaN heterostructures. Finally, results on GaN/AlN quantum dots were in accordance with the above conclusion.

**10:45 AM W12.6**
INFLUENCE OF INTERNAL ELECTRIC FIELDS ON THE GROUND LEVEL EMISSION OF GaN/AlGaN MULTI-QUANTUM WELLS. Annalisa Bonfiglio, Mauro Lomascolo, GianPiero Traetta, Roberto Cingolani, Aldo Di Carlo, Fabio Della Sala, Paolo Lugli, Andrei Botchkarev, Hadis Morkoc, Univ of Cagliari, INFM-Dept of Electrical & Electronic Engr, Cagliari, ITALY.

The aim of this work is the investigation of the emission properties of structures made by GaN/AlGaN multi quantum wells, namely the effect of strain and of the built-in electric field induced by spontaneous and piezoelectric polarization charges. A well-width dependent Stark-shift of the emission energy of the QWs has been observed in photoluminescence experiments. Such a field originates from the superposition of spontaneous polarization charge and piezoelectric charge in the heterostructure, and it can be exploited to tailor the emission energy of a QW-based optical device. We have performed a systematic investigation of GaN/AlGaN quantum wells grown on different buffer layers (either GaN or AlGaN, with typical well-widths of 2-4 nm) in order to clarify the role of strain, structural parameters and built-in field in determining the well-width dependence of the ground level emission energy. We find that identical quantum wells grown on different buffers (i.e., with different strain amounts in the quantum well) exhibit a relevant variation of the ground level energy (of the order of 50 meV) but a similar well-width dependence (about 400 meV of difference between samples with 2 nm and 6 nm of well-width with a relevant dependence on the photo-induced charge density, probably related to screening effects). The data have been quantitatively analyzed by an analytic envelope function model which accounts for screening and built-in field and by a full self-consistent Tight-Binding model. The comparison between theory and experiment reveals that the spontaneous polarization field is dominant over the strain and piezoelectric field effects, and basically determines the well-width dependence of the ground level emission.

**11:00 AM W12.7**
COMPARISON STUDY OF STRUCTURAL AND OPTICAL PROPERTIES OF $In_xGa_{1-x}N$/GaN QUANTUM WELLS WITH

DIFFERENT IN COMPOSITIONS. Yong-Hwan Kwon, G.H. Gainer, S. Bidnyk, Y.H. Cho and J.J. Song, Center for Laser and Photonics Research and Department of Physics, Oklahoma State University, Stillwater, OK; M. Hansen and S.P. DenBaars, Electrical and Computer Engineering and Materials Departments, University of California, Santa Barbara, CA.

We have systematically studied the structural and optical properties of $In_xGa_{1-x}N$/GaN multiple quantum wells (MQWs) with different In compositions of 8.8, 12.0, and 13.3% by means of high-resolution x-ray diffraction (HRXRD), photoluminescence (PL), PL excitation (PLE), stimulated emission (SE), and time-resolved PL spectroscopy (TRPL). The five-period MQWs were grown on sapphire substrates by metalorganic chemical vapor deposition. As the In composition increases, the superlattice satellite peak broadens and is observed to be 320, 470, and 600 arcsec, for the samples with In compositions of 8.8, 12.0, and 13.3%, respectively, in HRXRD measurements. In addition, PLE band edge broadens and is observed to be 23, 36, and 40 meV, respectively. The spatial variation of the SL period (possibly caused by intermixing and/or well size irregularity) and/or the fluctuation of alloy composition can be argued to be the responsible mechanism of broadening. These results indicate the deterioration of interface quality due to the difficulty of uniform In incorporation into the GaN layer. However, the samples with higher In compositions have lower room temperature (RT) SE threshold densities and lower nonradiative recombination rates, as determined by SE and TRPL experiments. The lower RT SE threshold densities of the higher In samples indicate that the effect of In suppressing nonradiative recombination overcomes the drawbacks associated with interface imperfection.

**11:15 AM W12.8**
EMISSION AT 290 NM FROM GaN QUANTUM WELLS GROWN BY MOCVD. Takao Someya, Katsuyuki Hoshino, Janet Harris, Koichi Tachibana, Satoshi Kako and Yasuhiko Arakawa.

We have measured photoluminescence spectra at 77 K from 1.5-nm-thick GaN quantum wells with $Al_{0.5}Ga_{0.5}N$ barriers, which were grown by atmospheric-pressure metal organic chemical vapor deposition. A clear peak was observed at 290 nm, which is shortest wavelength yet obtained from GaN/AlGaN quantum wells, to the best of our knowledge. The effective confinement energy, or difference between this recombination energy and the band gap of bulk GaN, is as large as 0.88 eV. Such strong confinement was achieved by reducing the well thickness down to 1.5 nm and increasing the Al content x in the $Al_xGa_{1-x}N$ barrier layers up to 0.5. Spectral linewidth was 190 meV. This value corresponds to the energy broadening induced by single monolayer fluctuation of well thickness, indicating that very smooth interfaces were obtained. The present tightly confined two-dimensional states should be promising for applications in deep ultra-violet detectors, telecommunication devices at 1.55 $\mu$m based on the intersubband transitions, and other advanced photonic devices.

**11:30 AM W12.9**
IDENTIFICATION OF As, Ge AND Se PHOTOLUMINESCENCE IN GaN USING RADIOACTIVE ISOTOPES. A. Stötzler, R. Weissenborn, M. Deicher, Fakultät für Physik, Universität Konstanz, Konstanz, GERMANY; and the ISOLDE Collaboration, CERN, Geneva, SWITZERLAND.

We report on photoluminescence (PL) experiments which unambiguously identify the chemical nature of optical transitions related to Arsenic, Germanium, and Selenium in GaN. The chemical assignment was achieved by using the element specific half-life of radioactive isotopes. If a transition is caused by a defect in which the parent or daughter isotope is involved the concentration of that defect and hence the PL intensity of the corresponding transition will change related to the half-life of the radioactive decay. In order to investigate As, Ge and Se defects in GaN epitaxial GaN layers were doped by ion implantation (energy 60 keV, dose $3\times10^{12}$ cm$^2$) with the radioactive isotopes $^{71}$As and $^{72}$Se at the on-line mass separator facility ISOLDE at CERN. The implantation damage was reduced by annealing the sample at 1273 K under $N_2$ atmosphere. The isotope $^{71}$As (half-life 64.28 h) decays first into $^{71}$Ge (11.43 d) which finally transmutes into stable $^{71}$Ga. The isotope $^{72}$Se decays via $^{72}$As (26 h) into stable $^{72}$Ge. This chemical transmutations were monitored with PL spectroscopy at 4.2 K. The PL spectras recorded within 30 days after implantation will be presented. The half-lifes resulting from exponential fits on our PL data for the optical transitions at 2.58 eV (As), 3.398 eV (Ge), and 1.49 eV (Se) are in excellent agreement with the half-lifes of the isotopes. This correlation also shows that each of these luminescence centres involves exactly one As, Ge or Se atom.

**11:45 AM W12.10**
ENHANCEMENT OF 1540 NM Er3+ EMISSION EFFICIENCY IN Er-IMPLANTED GaN BY Mg-CODOPING. S. Kim, Department of Electrical Engineering, Korea University, Seoul; S.J. Rhee, X. Li, J.J. Coleman, and S.G. Bishop, University of Illinois at Urbana-Champaign, Urbana, IL.

Recently, selective photoluminescence (PL) and photoluminescence excitation (PLE) spectroscopies carried out at 6K on the ~1540 nm 4 I 13/2 to 4 I 15/2 emissions of Er3+ in Er-implanted GaN revealed the existence of nine different Er3+ centers and associated PL spectra[1-4]. Several of these centers are excited by broad-band, below-gap absorption bands associated with a variety of Er-defect/impurity complexes, with subsequent nonradiative energy transfer to the Er3+ 4f electrons. It was demonstrated [3,4] that less than 1% of the Er atoms are involved in these Er-defect/impurity complexes which dominate the Er3+ emission spectra excited by above-gap and broad-band below-gap absorption because of their larger cross sections for both carrier capture and optical absorption. This means that the trap-mediated above-gap pumping of Er3+ emission in Er-implanted GaN by either optical or electrical means excites only a tiny fraction of the total optically active Er3+ sites. On this basis we suggested[4] that the efficiency of above-gap optical or electrical excitation of Er3+ in GaN might be improved by identifying appropriate co-dopants that promote the formation of high capture cross section complexes with the Er atoms. In the present work we show that the Er3+ PL and PLE spectra of Er-implanted Mg-doped GaN exhibit a significant enhancement of the so-called violet-pumped Er3+ emission spectrum [1-4]. This Er3+ center is selectively excited by a characteristic ~2.8-3.4 eV (violet) below-gap PLE band. More importantly, the violet-pumped PL center dominates the above-gap excited Er3+ PL spectrum of Er-implanted Mg-doped GaN, whereas it was unobserveable under above-gap excitation in Er-implanted undoped GaN. These results appear to confirm our hypothesis that appropriate co-dopants can increase the efficiency of trap-mediated above-gap excitation of Er3+ emission in Er-implanted GaN. 1. S. Kim, S.J. Rhee, D.A. Turnbull, E.E. Reuter, X. Li, J.J. Coleman, and S.G. Bishop, Appl. Phys. Lett. 71, 231 (1997). 2. S. Kim, S.J. Rhee, D.A. Turnbull, X. Li, J.J. Coleman, S.G. Bishop, and P.B. Klein, Appl. Phys. Lett. 71, 2662 (1997). 3. S. Kim, S.J. Rhee, X. Li, J.J. Coleman, S.G. Bishop, and P.B. Klein, J. Elec. Mats. 27, 246 (1998). 4. S. Kim, S.J. Rhee, X. Li, J.J. Coleman, and S.G. Bishop, J. Elec. Mats. 28, 266 (1999).