SYMPOSIUM W
GaN and Related Alloys
November 28 – December 3, 1999

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*Invited paper
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 $\sim 10^5 \text{cm}^{-2}$ to $\sim 10^3 \text{cm}^{-2}$. The reverse bias leakage current is reduced by 3 to 4 orders of magnitude for devices on LEO GaN regions compared to devices on the InGaN regions. These results indicate 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 kHz cm$^{-2}$ for InGaN on GaN on sapphire substrates to 4.8 kHz cm$^{-2}$ for laser diodes grown on LEO GaN on sapphire. The lasers on the LEO GaN showed a low threshold current density both above the SiO$_2$ mask regions and below the coalescent front 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 LD characteristics were measured for different temperatures, yielding a characteristic temperature of 120°C. 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 GaN 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 tilt angles seen, which are greater than 1°. The laser structures on LEO GaN have a reduced dislocation density compared to those grown on sapphire substrates. TEM and AFM micrographs show 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. Cruwen, J.S. Speck, U.K. Mishra, I.A. Coldren and S.P. DenBaars, Materials 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 vertical integration of high quality p-type layers. This work investigates AlGaN/GaN strained layer superlattices used as cladding layers in AlGaN 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 superlattices as cladding layers was superior to laser structures with bulk AlGaN cladding as seen by atomic force microscopy (AFM) and x-ray diffraction (XRD). The superlattice cladding has reduced edge dislocation density, 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 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 8.2 to 12 kA/cm$^2$. Transmission line model measurements revealed an increase in lateral conductivity with superlattice period which leads to increased carrier recombination at the sidewall of the laser ridge, thus reducing threshold current density.

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

Microdisk- and microcavity light-emitting diodes (LED) have been fabricated from metalorganic chemical vapor deposition (MOCVD) grown p-n junctions and InGaN/GaN quantum wells. Photolithographic patterning and indium-coupled plasma (ICP) dry etching have been employed to create these 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 optical properties of the nitride LED layer 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 microLEDs. The EL emission properties under excitation by a laser are almost identical with those under optical 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. We suggest that the high brightness and high brightness per area, the total light output can be enhanced by replacing the conventional broad-area LEDs with micro-size LED arrays. Optical pumping was also employed to study the optical confinement effect in a 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 micro-disk cavities. The WG modes are the most visible 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 array or micro-size display, and micro-size LED arrays, microdisk and microring laser diodes, will be discussed.

10:45 AM W1.6
SPATIAL RESOLVED ELECTROLUMINESCENCE OF InGaN MQW-LEDs. Veit Schweger, Christopher Kirchner, Matthias Seybold, Markus Kunig, University of Ulm, Dept. of Optoelectronics, Ulm, GERMANY. Peter Fischer, Jürgen Christian, Margit Zacharias, Otto-von-Guericke University, Institute of Experimental Physics, Magdeburg, GERMANY.

Electroluminescence (EL) is the most significant measure for light-emitting direct-gapLEDs since it provides detailed properties of the bulk material 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 integrated EL, corresponding to an InGaN active layer. The output power of the UV-LEDs is in the mW range. The μ-EL-characterization is performed as a function of injection current densities and the emission is investigated from the epilayer side as well as from substrate side. Spatially resolved wavelength images reveal emission peaks between 410 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 instability of these substrates is obtained from the local redshift to 419 nm of the area beneath the contact, caused by heating, thus reflecting the thermal distribution in the device.

11:00 AM W.7
REDUCED TURN-ON VOLTAGE FOR GaN-Er LEDs. J. Hekenfeld, M.J. Garret, D.S. Lee, R. Béckaj, A.J. Steck, 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 1V, where we use the term turn-on voltage to signify the condition where the radiative 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 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 (~0.33 cm-thick) Si substrates instead of standard (~10 cm-thick) wafers, (b) decreasing the GaN layer thickness from the 1500-2000 nm range to the 300-700 nm range. We have found that increasing the Si substrate doping in a more pronounced rectifying electrical characteristic for the devices the 300-700 nm range this is accompanied by reduction in optical turn-on voltage from a 40-120 V range to 10-15V for the heavily doped substrates. Further reduction in turn-on voltage was obtained by reducing the GaN-Er layer. For example, a heavily doped 300 nm film displays an optical turn-on voltage of only 0.5 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 higher input power (albeit at a lower efficiency 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 W.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 high-index nitride DBRs have been the way to the realization of high finesse resonators (dual-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 ~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 96% at 465nm utilising 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 tensile stress built up in the AlN layers. Asymmetric structures with AlN layers thicker than a quarterwave and GaN layers thinner than a quarterwave have been grown on (0001) sapphire (0001) and experimental data show that high reflectance is still possible although the bandwidth is slightly reduced. [1] H.M. Ng, D. Doggallapudi, E. Higouros and T.D. Moustakas, Appl. Phys. Lett. 74, 1836 (1999). [2] T. Sugawa, T. Ishikawa, and Y. Arakawa, Appl. Phys. Lett. 70, 3623 (1997). [3] H. Longer, A. Bursi, J. Simon, N.T. Pelekosan, O. Kozorol, R. Andre and L.S. Dang, Appl. Phys. Lett. 74, 3610 (1999).

11:30 AM W.9

The successful synthesis, fabrication, and testing of two types of AlGaN heterojunction p-n photodiodes that operate in the range from 380-365 nm is reported. The first type consists of a 1.5 μm Al0.6 Ga0.4N/Si n-type layer grown by MOVPE onto a low temperature AlN buffer layer on sapphire. On top of this is a 0.2 μm undoped i-GaN active layer followed by a 0.5 μm p-type GaN layer. The second type is an n-type 1.3 μm thick Si0.5 Al0.5 Ga0.4N/Si layer, followed by a 0.2 μm p-type undoped i-Al0.16 Ga0.84N active layer and a 0.5 μm p-type Al0.16 Ga0.84N:Mg top layer. Square mesas of area A = 4 x 10^-3 cm^2 were obtained by reactive ion etching using C4F8/TiAl and N2/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. RA values were also obtained for each sample. The detector spectral sensitivity D^* was then calculated using standard photodiode equations for a noise-limited detector. The GaN/Al0.5 Ga0.5 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%. RA values up to 1.5 x 10^7 Ω-cm^2 were obtained, corresponding to D^* = 6.1 x 10^5 cm^-2 Hz^-1/2 W^-1 at 356 nm. This is the largest D^* value ever obtained for any semiconductor photodiode at any wavelength, and the result is a factor of six of D^* values for UV-enhanced photomultiplier tubes. The Al0.16 Ga0.84N/Al0.5 Ga0.5 N p-n photodiodes exhibited a UV spectral response between 380 and 320 nm with a peak spectral responsivity R = 0.09 A/W at 305 nm, corresponding to an internal quantum efficiency of 42%. RA values of 2.8 x 10^6 Ω-cm^2 were obtained such that D^* = 1.6 x 10^4 cm^-2 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 below 10^-4 A/W. This work is supported by grants from DARPA and ARO.

11:45 AM W.10
LOW-INTENSITY UV PHOTODETECTORS BASED ON HIGH QUALITY AlGaN USING LOW-TEMPERATURE AlN INTERLAYER. Motoki Ikeya, Nobuhiko Hayashi, Takanori Kishima, Dept of Electrical and Electronic Engineering, Meijo University, Nagoya, JAPAN; Tohoku-Daiichi Dettexpro, High Tech Research Center, Meijo University, Nagoya, JAPAN; Hiroshi Amamoto, Isuzu
t has been correlated with the ratio of wing width (w) to height (h), which is directly dependent on growth conditions (e.g., V/H ratio, temperature) and fill factor of the growth process (open 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 larger areas (2 in.) $\text{SiO}_2$/$\text{GaAlO}_3$ wafers by low-pressure metaldiorganic chemical vapor deposition (MOCVD) before and after confection. Using scanning electron microscopy (SEM), x-ray diffraction (XRD), transmission 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 stripes were annealed and no additional growth of $\text{GaN}$ is grown, it is found with XRD that a peak splitting due to tilt is no longer detectable. TEM and AFM results show that few dislocations (with a linear density of $<4 \times 10^3 \text{cm}^{-1}$) are formed at confection fronts.

2:15 PM W23/0.1.3
FABRICATION OF GaN WITH BURIED TUNGSTEN [W] STRUCTURES USING EPITAXIAL LATERAL OVERGROWTH (ELO) AND THEIR CHARACTERIZATION. Kazumasa Hiramatsu, Hideo Miyake, Atsushi Motogoto, Dept of Electrical and Electronic Engineering, Mie Univ, Mie, JAPAN; Yasuoishi Kawaiuchi, Shingo Nishida, Nobukawa Sawaki, Dept of Electronic Engineering, Nippon Univ, Nippon, JAPAN; Yousuke Ikeda, Tokyo Chemical Co Ltd, Tsubak, JAPAN.

Epitaxial lateral overgrowth (ELO) of GaN with tungsten [W] mask provides a superior alternative to HVPE or HYPE in 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 performed in MOVPE and HVPE. The buried lateral overgrowth of GaN by HVPE 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 $<1120>$ and $<1100>$. Optical and crystalline characteristics of ELO-GaN are investigated by means of AFM, CL, TEM, and x-ray rocking curve. Thus, those characteristics show evidence of highly crystalline quality with atomically flat surface, uniformly perfect excitonic emission, no oxide tinking 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 $<1100>$. The W has a severe catalytic effect to attack the underlying GaN layer with a hydrogen ambient at high temperature. To prevent decomposition of GaN layer, we employed ELO of GaN at temperatures below 1100°C under a low reactor pressure ($<300$ or $<300$ Torr) which allows us to enhance the lateral overgrowth. Consequently, the W mask was removed without damage to the underlying GaN and their crystalline and electrical properties were characterized for aiming at the SIT device.

2:30 PM W24/0.1.4
ADVANCED PENDEO-EPITAXIAL GROWTH OF GaN THIN FILMS ON Si[001] AND Si[111] SUBSTRATES VIA METALORGANIC CHEMICAL VAPOR DEPOSITION AND THEIR STRUCTURAL, MICROSTRUCTURAL, OPTICAL, AND ELECTROPHYSICAL CHARACTERIZATION. T. G. 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 surfaces into the regrown areas. The use of a mask can cause the formation of boundaries at the interface of two growth fronts and a crystalllographic tilt in the adjacent regions that have a significant impact on the performance. The effect of the dislocation density in the as-grown GaN films grown on Si substrates usually show a high density of dislocations caused by the difference in the coefficients of thermal expansion of the two materials. Moreover, the processing steps to achieve PE growth on the aforementioned substrates have been investigated to reduce the formation of confluence boundaries, the tilt in the overgrown regions, and the cracking in the overgrown 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 papers.
3:30 PM W2.6/16.1
DISLOCATION MECHANISMS IN THE GaN LATERAL OVERGROWTH BY HYDROGEN PHASE EPITAXY

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 were 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 coalescence 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 relieve 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 direction. This multiplication and pickup 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 (~8 degrees) when the growth is at 1100°C and becomes smaller (~5 degrees) at 1050°C, with the coherence 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. The present stress analysis 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.

4:00 PM W2.7/16.1
GaN LAYERS GROWN BY NANO EPITAXIAL LATERAL OVERGROWTH TECHNIQUE ON POROUS GaN. M. Mykhaylenko, A. Titkov, A. Kryzhovskiy, A. Zubrik, V. Ramnikov, V. Dmytrenko, N. Kuzmyk, and I. Bidin, Institute for Physics of Microstructures, National Academy of Sciences of Ukraine, Kyiv, Ukraine; A. Tsvetkov, S. Stepancev, A. Cherenkov, I. Kotsosova, Crystal Growth Research Center, St. Petersburg, Russia; and V. Dmitriev, TDI, Inc., Gainesville, 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 talk, we describe a novel concept, 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 oxidation of GaN grown directly on Si substrates. 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 Si-SC 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.

4:30 PM W2.7/16.2
SELECTIVE AREA GROWTH STUDIES OF COALESCEENCE MECHANISMS IN GaN CVD. Michael E. Bierbaum, Michael E. Coltrin, Christine C. Willim 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 [11-20] facets, occurring at the point of convergence between adjacent islands, can open an avenue for growth in the more favorable [11-20] direction. This mechanism, growth takes place only in a planar at a step-flow fashion on these facets. However, rapid accumulation of these layers can drive growth in the opposing [11-20] direction as well as the [11-20] direction at an unexpectedly high rate. These observations explain in molecular terms how rapid surface smoothing of GaN occurs when this is often observed in the presence of the otherwise slow growing [11-20] facets in hexagonal ice. Specifically, since nucleation of each layer begins at facet intersections, low surface area facets can multiply more quickly until adjacent facets have coalesced. This enhancement effect results in pits of high symmetry (hexagon) during the later stages of coalescence. (Sandia is operated by Sandia Corporation, a Lockheed Martin Company, for the USDOE under DE-AC04-94AL85000.)

4:45 PM W2.11/16.1
DISLOCATION ARRANGEMENTS IN THICK LEO GaN.
K.A. Dunn, S.E. Babcock, D.S. Stone, Materials Science & Engineering Dept, Lehigh University, Bethlehem, PA; Ning Zhang, T.F. Kuech, Chemical Engineering Dept, University of Wisconsin-Madison, Madison, WI.

Diffusion-contrast transmission electron microscopy and microdiffraction techniques were used to examine and characterize dislocation arrangements in thick (~15 μm) GaN films grown by MOVPE. The windows in the LEO substrate were 1.5 μm wide with a 12 μm spacing and their long axis oriented along the [11-20] direction of underlying GaN on sapphire.
Trimehtylgallium (TMG) 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 growth rate of the polycrystalline film is a beveled rectangle with side walls parallel (11 1 20) and bevels on (11 2 1) 1/3. 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 from the substrate. These dislocations form a network from the substrate, which is also the thickness by which almost all of the original threading dislocations have bent into the (100) plane. Sets of loops sweep out an approximately triangular bevel shape 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-MSEC at UW provides partial support for the UW electron microscopy facilities.

SESSION W3: POSTER SESSION: GROWTH, STRUCTURAL, CHARACTERIZATION, SURFACE STUDIES, THEORY, DOPING

Chuantian Huang, Annette R. Randall, M. Feenstra, Thomas H. Meyers and Michael S. Shur
Monday Evening, November 29, 1999
8:00 PM
Exhibition Hall D (H)

W3.1 A TEM STUDY OF GaN GROWN BY ELOG ON 6H SIC.

The ELOG technique has brought about the possibility to decrease the dislocations densities from 10 to 10 to less than 10 cm² in GaN layers grown on sapphire. Whereas, the misfit between GaN and 6H-SiC is 3.5%, instead of 16% over growth on sapphire, the epilayer laxis 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 completely coalesced layer. They analysed ELOG islands that have always the same hexagonal shape, limited by [10-11] facets. It is then pointed out that the [61-20] 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 prismatic plane, whereas n-type 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 LIDS.
Koen Jacobs, Jan Chynho, Ingrid Morshuis, Pies Demeester, Dept. of Information Technology, University of Gent, Gent, BELGIUM; Edward J. Thrush, Thomas Swan & Co. Ltd., Harston, Cambridge, UNITED KINGDOM.

Epitaxial Lateral Growth 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 optoelectronic device performance. Recent progress with ELOG has already contributed to the realization 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 the previous 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 FWHM around 200 arcsec, which is a 30% reduction with respect to our ELOG results. PL characterization 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 FOLLATY DETERMINATION FOR MOCDV GROWTH OF GaN ON Si (111) BY CONVERGENT BEAM ELECTRON DIFFRACTION. L. Zhang, H. Marchand, S.P. Denbass, U.K. Majra, 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) substrate have been demonstrated. Basic structural properties were characterized. The stripe morphology could be grown 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 GaFace. In this presentation the polarity of laterally overgrown GaN films grown by low-pressure metalorganic chemical vapor deposition (LP-MOCVD) on Si(111) with AIN buffer layer was studied using Convergent Beam Electron Diffraction (CBED). The 180 nm thick AlN buffer was deposited at 900°C using TMAI and NH₃ as precursors and was covered with 180 nm thick SiO₂ in which 5 μm wide stripes separated by 2 μm were exposed using standard photolithography and wet etching. LEO GaN stripes were obtained by performing a regrowth at 800°C using TMGa and NH₃. CBED patterns were obtained at 200 kV for the <111> zone axis. When indexing the diffraction pattern with the 180° degree inversion rule and dislocations pattern was considered. The experimental CBED patterns were taken from LEO GaN regions in which the threading dislocation density in less than 10 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 Microscope 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 was 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 Okyoung Nam, Cheolsoo Seon, Ighyeon Kim, Yongjo Park, Taeil Kim, SATH国家原子力研究所 (Korea); Photonics Lab, Swayon, KOREA.

Lateral epitaxial overgrowth (LEO) technique has extensively been studied by many research groups for GaN epitaxial film. Many reports have 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 LEDs on the laterally overgrown GaN (ELOG). However, the recent report showed that the arrays of dislocations are formed in the coalesced regions over the SiO₂ 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. Tiling 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 was explained 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 SiO₂ mask and LEO GaN.

W3.5 LATERAL EPITAXIAL OVERGROWTH VS. PENDEO-EPITAXY OF GaN STRUCTURES: A FINITE ELEMENT ANALYSIS

Takashi Itoh, Tsuneyoshi Tani, Kenichiro Kasahara, and Kenichi A. Jones Sensors and Electronics Directorate, Army Research Laboratory, AMSRL-SE-EM, Adelphi, MD, United States of America; 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 growth exhibits 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 unclear how 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 is the (1210), (1010), or (1011) planes of the GaN, defined by the electric field and the data of time and temperature dependence of the propagation of the vertical and lateral GaN growth fronts, and examination of the morphology of the surfaces, side facets, and interface of the LEO and PE-GaN stripes with the underlying and adjacent interfaces, reveal 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 microscopy (TEM) and atomic force microscopic (AFM) studies of the top surface of the 0.45 pm thick SiO2 layer.

W3.3 STRUCTURAL AND OPTICAL CHARACTERIZATION OF LATERALLY OVERGROWN GaN. Zheng, Zong, Y. G. Zhou, B. Shen, S. G. Liu, Y. Shi, Y. D. Zheng Laboratory of Solid State Microelectronics 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-metallographic vapor phase epitaxial grown GaN film on C-plane sapphire substrate etched by 0.45 pm thick SiO2 layer. The pattern consists of parallel stripes along 1 < 100> directions exposed to the growth ambient with the period of 12 pm and the mirror of 4 pm. GaN are grown by HVPE using an incident reaction source and carrier gases under the condition of Tg=1100°C, V/H=33, and mole fraction of NH3/N2=9.076. The epitaxially lateral overgrowth of GaN on SiO2 area is observed. After 1 hour growth, a planar ELO GaN film with the thickness of 10 pm is obtained. Micro-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. Micro-Raman scans taken in both ELO and non-ELO areas clearly show E2(LO) phonon scattering peaks. AFM image indicate that the step termination is too little to be detected in a 2x2 pm area in the ELO region. Low-temperature PL reveals that there are luminescence bands 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 area. TEM observation shows that the dislocation density is very low in the ELO region.

W3.4 HYDRIDE VAPOR PHASE EpITAXY (HVPE) of GaN on Self-Faceted SAPPHIRE SHAPED RIBBON CRYSTALS. V. A. Ivanovskii, M. G. Mudrochnov, A. B. Buzhinsky, P. N. Nikitin, A. E. Nikolaev, V. M. Krimov, P. Antov, Koldor Institute, St. Petersburg, RUSSIA, I. S. Kotsoukov, Crystal Growth Research Center, St. Petersburg, RUSSIA.

Appropriate chemical and mechanical properties accompanied with commercial availability have made sapphire one of the most popular substrate material for GaN epitaxy. Even a little change in mechanical preparation of the substrates (a difference in treatment duration) may lead to unpredictable results of the epitaxy. To avoid any mechanical treatment, or contamination of the surface of sapphire crystals is preferred to be used for GaN epitaxy. The proper technique to produce substrates having such surfaces is the Stepovak (EFG) self-faceted-ribbon growth method. In this work, substrates cut from 10 mm wide (0001) Stepovak sapphire ribbon sapphire crystals were used for subsequent HVPE growth of GaN without any buffer layer. Hot-wall horizontal reactor was used to deposit 20 pm thick GaN layers simultaneously on the Stepovak (S) and referred commercial Union Carbide (UC) substrates. The AES and RHEED measurements were done to analyze elemental and structural characteristics of the substrate surface before and after chemical treatment prior the epitaxy. The XRD measurements performed in scanning geometry at 0.02 degrees were utilized to evaluate the structural perfection of the HVPE grown layers. The results showed that the GaN peaks of the XRD patterns of GaN grown on the S-substrate (cleaved from the surface contamination by chemical etching) is about 1.5 times narrower than that of the UC-substrate (e.g., 434 arcsec and 629 arcsec, respectively). So, the use of the Stepovak self-faceted sapphire substrates improves the structural perfection of the GaN epitaxial layers. Rather surprising, this result was obtained on the Substrate having growth steps with a height of 2554-1400 A.


Results of GaN epitaxial growth on bulk-like GaN substrates are reported. At first the GaN layers were grown in the open tube chloride system GaCl3-NH3-H2 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 further analysis. In one case, n-GaN epilayers and p-n junctions were grown by low pressure MOVCD 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 surfactant and optimal thickness of the buffer layer was shown. The combined 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 IN NITROGEN AND LIQUID AMMONIA PRESSURE. A.Y. Pylagov, A.V. Govorov, N.B. Smirnov, M.G. Mil'vidskii, Institute of Rare Metals, Moscow, RUSSIA; V.A. Suhkoveev, V.A. Ivanov, A.F. Ioffe Physico-Technical Institute RAS, St.-Petersburg, RUSSIA; V.A. Dmitriev, TDI, Inc. Gatchina, RUSSIA.

Crystals of GaN of about 20 mm in size were grown from liquid phase at reduced pressure (below 2 atm.) by seed 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 inclinations. The electron concentration in the crystals is on the order of 10^18 cm^-3 with the electron mobility of about 30 cm^2/Vs. MCL spectra show a very pronounced yellow luminescence band and a weak near-band-edge luminescence at 3.35 eV (300K) and 3.42 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 blue and green regions of the macrophotographs allows localization 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 Olesnikiy, Vladimir Bul'gin, Fei Ling Wang, Peter Vakhitov, Peter Norris, Zy Applied Technologies, Woburn, MA.

Combining ferroelectric oxide materials with III-nitride WBG semiconductor devices is 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 optical properties of high quality oxide films of PLZT family on n-GaN/C-A12O3 structures. Single-phase 0.5-5 μm thick layers with compositions 1/5/2/48 and 9/8/25 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 the presence of the metal oxide buffer layer. Ferroelectric hysteresis loops, optical phase shift, LE and C-AX measurements were used to characterize the PLZT/GaN capacitors. Hysteresis loops were found to be either symmetrical or asymmetrical with respect to zero bias depending on the introduction of the thin oxide buffer grown prior PLZT growth. Values of PN were in 25-40 μC/cm² range. The PLZT/GaN structures exhibit hysteresis electro-optic behavior typical for ferroelectrics. We measured a strong E-O effect with large field induced birefringence. The obtained ~Δn value was comparable with the best reported for films of the same composition grown on single crystal sapphire substrates.

W3.15 HYDRO AND MOVPE GALLIUM NITRIDE GROWTH ON SLIGHTLY MISORIENTED SAPPHIRE SUBSTRATES. Olivier Pavlidis, Volker Wagner, Hans-Jürg Bhulmann and Marc Rieger, Institute of Micro- and Optoelectronics, Swiss Federal Institute of Technology, Lausanne, SWITZERLAND.

Due to the lack of suitable GaN substrates, (0001) exact Al₂O₃ is the principal substrate used for the realization of GaN-based devices. To our knowledge, MOVPE of GaN on slightly misoriented Al₂O₃ and none deals with HVPE on such substrates. However, for other III/V compounds like GaAs or InP, it has 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 superstructure of the gas phase is quite small in the hydride technique as opposed to the MOVPE systems and growth occurs near the thermodynamic condensation layer as shown 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 growth hiklos which are typical for HVPE GaN layers (0001) sapphire substrates are reduced by more or less parallel micro-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 and 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 HYPID VEAPOR PHASE HOMOEPITAXIAL GROWTH OF GaN ON MOVPE-GROWN TEMPLEATES. T. Paskova, E.B. Svedberg, S. Tungsumit, IFM, Linköping University, Linköping, SWEDEN; R. Becard, M. Heiken, Aixtron AG, Aachen, GERMANY; B. Armazov, S. Fomov, Faculty of Physics, Sofia University, Sofia, BULGARIA; A. Henry and B. Mommer, 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 optimization 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 vapor deposition (MOVCD) grown GaN templates with subsequent homoepitaxial GaN growth, only preliminary data have been presented on the use of MOVCD GaN templates in hydride vapor phase epitaxial (HVPE) growth of thick GaN layers. We report on an improved quality of thick HVPE GaN grown on MOVCD template layers compared to the material grown directly on sapphire. The GaN layers with a thickness in the range of 2.8-4μm were grown in a conventional HVPE system at growth temperature of 1060°C. The reference samples were grown using a nitridation pretreatment of the sapphire. The MOVCD-GaN template layers with a thickness of 2μm were grown in the Aixtron application laboratory. All samples grown on template layers exhibit significantly smoother film surfaces and a reduction of the dislocation density. A change in the close packed crystallographic character to a pure screw or pure edge type of dislocations has been revealed by both atomic force microscopy and transmission electron microscopy. 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.

W3.16 THE NATURE AND IMPACT OF ZnO BUFFER LAYERS ON THE INITIAL STAGES OF THE HYDROGEN FREE MOVPE EPITAXY OF GaN. Stanley Gu, James Scott, 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 material 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 ZnO interlayer or buffer layer. In many cases, the ZnO layer has been reported not to survive the initial heating and pro-growth treatment and is not reported to be present in the final epitaxial multilayer 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 pro-growth anneal but subsequently reverts disordered under routine pro-growth annealing conditions on sapphire. 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 the ZnO-derived interface 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.
V3.16 VISIBLE AND INFRARED EMISSION OF GaNEx THIN FILMS GROWN BY METALLOrganIC CVD: GROWTH CONDITIONS AND ELECTRICAL PROPERTIES. Hong Chen, K-Guamurum, and M.E. Kordesch, Department of Physics and Astronomy, Ohio University, Athens, OH.

In this paper, we report the investigation of E-deposited GaN grown on sapphire and silicon substrates by sputtering with different doses of erbia. The film properties were characterized by X-ray diffraction (XRD), optical transmission (FTIR), Rutherford backscattering spectroscopy (RBS), cathodoluminescence (CL), and photoluminescence (PL) spectroscopy in the visible and infrared (IR) spectral region. The film properties indicate that the as-deposited GaN is crystalline and exhibits a tetragonal structure with a high degree of strain. The XRD data show a decrease in the full width at half maximum (FWHM) of the GaN (002) peaks with increasing de position rate. The PL spectra exhibit a broad emission band centered at ~420 nm, which is attributed to the GaN bandgap emission. The RBS data show a good agreement with the film composition, indicating that the GaN films grown on the substrates have a high quality and good crystallinity.

V3.17 GALLIUM NITRIDE IN A MESOPOROUS MATRIX OF MCM-41. Holger Winkler, Richard Fischer, Ruh University Bochum, Inst. Of Inorganic Chemistry, Bochum, GERMANY; Roland Schmedel, Heinrich-Heine University, 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, such as a wide and direct bandgap of 3.45 eV, high compressibility, and high thermal conductivity. The device fabrication process involves the formation of thin films of GaN realized by MOCVD or MBE, which has been well established for the growth of GaN on sapphire substrates. The GaN films are then treated with UV light to enhance their optical properties. The MOCVD process is preferred for the fabrication of GaN thin films due to its scalability and low cost. The MOCVD process involves the deposition of the GaN film on a sapphire substrate, and the growth parameters such as temperature, pressure, and gas flow rate are optimized to achieve the desired film properties.

W3.18 GROWTH KINETICS OF GaN THIN FILMS GROWN BY MOVPE USING SINGLE SOURCE PRECURSORS. Roland A. Fischer, Anjani Devi, Wolfgang Rogge, Andreas Wehlert, Anorgametische Chemie II, Ruh University Bochum, Germany.

We report the epitaxial growth and characterization of GaN thin films using the single source precursor bis(trimethylsilyl)dimethylamine (BTS) and a combination of bromo- and anisole-terminated group V precursors. The growth was carried out using a metalorganic vapor phase epitaxy (MOVPE) reactor, and the films were grown on c-axis sapphire substrates at a temperature of 870°C. The growth rate was optimized to achieve a high quality GaN film with a smooth surface and good crystallinity. The X-ray rocking curve measurement showed a full width at half maximum (FWHM) of 0.6°, indicating a high degree of epitaxy. The PL spectrum showed a strong emission peak at 4.5 eV, which is attributed to the GaN bandgap emission. The optical properties of the GaN films were characterized using photoluminescence spectroscopy, which showed a high quantum efficiency and a low defect density.

W3.19 SUPPRESSION OF GAS PHASE ADDUCT REACTIONS IN THE MOVPE OF GaN. A. Thon, T. Friedl, M. Ishii, T. F. Kuech, Department of Chemical Engineering, University of Wisconsin-Madison, Madison, WI.

Trimethyl gallium-trimethylamine (TmGa/TmN) adduct formation and decomposition are alternative reaction pathways for MOVPE of GaN. To study this process, we performed experiments using a combination of metalorganic vapor phase epitaxy (MOVPE) and mass spectrometry. The results showed that the adduct formation and decomposition is inhibited by the presence of TmN. The adduct formation involves the reaction between TmGa and TmN, resulting in the formation of a gallium nitride complex. The adduct decomposition involves the reaction between TmGa and TmN, resulting in the formation of GaN and Tm3N4. The adduct formation and decomposition are highly dependent on the growth conditions, such as temperature, pressure, and gas flow rate. The adduct formation and decomposition can be suppressed by adjusting the growth conditions, which can be used to control the growth rate and film quality.

W3.20 GASES PHASE CHEMISTRY AND MATERIAL PROPERTIES OF METAL/ORGANIC VAPOR PHASE EPITAXY OF GaN. J. M. Redwing, T. F. Kuech, Department of Chemical Engineering, University of Wisconsin-Madison, Madison, WI.

GaN-based devices have been fabricated successfully using the metalorganic vapor phase epitaxy (MOVPE) technique. However, many fundamental growth-related problems remain unresolved. The metalorganic vapor phase growth of GaN is complicated by the extensive and pervasive chemical interactions between the growth species and the substrate. The metalorganic vapor phase growth process is characterized by the formation of gaseous precursors, which are transported to the substrate surface through a series of chemical reactions. The chemical interactions between the gaseous precursors and the substrate surface can significantly affect the growth rate and film quality. Understanding the chemical interactions between the gaseous precursors and the substrate surface is crucial for developing novel growth techniques and improving the efficiency of GaN-based devices.

W3.21 GROWTH OF HIGHLY ORIENTED HEXAGONAL GALLIUM NITRIDE FILMS BY MOVPE USING NOVEL SINGLE SOURCE PRECURSORS. J. M. Redwing, T. F. Kuech, Department of Chemical Engineering, University of Wisconsin-Madison, Madison, WI.

We report the growth of GaN films using a novel single source precursor, bis(trimethylsilyl)amine (BTS). The growth was carried out using a metalorganic vapor phase epitaxy (MOVPE) reactor, and the films were grown on sapphire substrates at a temperature of 870°C. The growth rate was optimized to achieve a high quality GaN film with a smooth surface and good crystallinity. The X-ray rocking curve measurement showed a full width at half maximum (FWHM) of 0.6°, indicating a high degree of epitaxy. The PL spectrum showed a strong emission peak at 4.5 eV, which is attributed to the GaN bandgap emission. The optical properties of the GaN films were characterized using photoluminescence spectroscopy, which showed a high quantum efficiency and a low defect density.

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Volatil single precursors were synthesized by the reaction of trihexyl(2,6-dialkylpyridine)alkylalumnum halides (H2NNHCH3Cl) followed by the reaction with NaN3. Novel alkylalkylamidium halides adducts were obtained as liquids or volatile solids depending on the alkyl groups of the gallium metal. The physical properties of the precursors indicated that they were reasonably suitable as single precursors for MOCVD. These precursors with large N/Ge ratios might overcome the nitrogen deficiency commonly observed in the GaN films produced by metal organic chemical vapor deposition (MOCVD), and they were employed to grow GaN films on Si substrates in the temperature range 500-800°C by MOCVD. The deposited GaN films were characterized by X-ray photoelectron spectroscopy (XPS), X-ray diffraction (XRD), double crystal X-ray diffraction (DCXRD), X-ray photoelectron microscopy (XPD) and photoluminescence (PL) spectroscopy. The XRD results have shown that the films grew with the highly preferred orientation of (0001) direction without any rhombohedral or prismatic facets. Other structural properties such as surface morphology, full width at half maximum (FWHM) of the GaN (1000) 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. Brown, J. Randall Coughlin, Jun Han, Jeffrey J. Figiel and Terence 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 results observed in condensed phases. We have examined the interactions between a number of precursors in the gas phase using infrared spectroscopy (FTIR) and mass spectrometry and by monitoring pressure changes which occur upon mixing. Our results provide evidence for a reaction occurring between bis-dicyclopentadienyl magnesium (MgCP2) and ammonia and water from room temperature to 500°C. MgCP2 also does not react with trimethylgallium. This suggests that the formation of solids associated with MgCP2 may be due to cooling and pressure gradients effects in the reactor inlet. The reactions between NH3 and TMG and trimethylgallium (TMG) were measured as a function of temperature. Mass spectra of both the TMG NH3 and the TMG NH3 adducts were observed. However, evidence for these species decomposing to ammonia and carbon monoxide 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 under contract with the U.S. Department of Energy). Under DE-AC04-94AL85000.)

W3.23

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 61 arcsec). This high quality was obtained by the introduction of an AlN/GaN 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 AlN 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, F2 x-ray diffraction scans revealed a structural transition of the underlying AlN layer during the deposition of the AlN layer. If the total pressure during the AlN growth was below 200 mbar then the AlN(111) reflection is clearly seen in the X-ray spectra independently 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 AlN(111) reflection in the X-ray spectra was strongly reduced or even vanished while new reflections emerged with an in-plane peak position similar to the AlN(111) reflections. In order to get more insight into this interesting structural transition, such transformed layers are currently studied by transmission electron microscopy.

W3.24
GROWTH AND CHARACTERIZATION OF GaN THIN FILMS ON Si(111) SUBSTRATES USING SiC INTERMEDIATE LAYER. K. J. Lee, Y.-J. Park, K. C. Kim, S. H. Lee, M. Yang, and Y. K. Lim, Dept. of Semiconductor Science and Technology, Semiconductor Physics Research Center, Chonbuk National University, Jeonju, KOREA; K. C. Noh, Dept. of Chemical Engineering, Semiconductor Physics Research Center, Chonbuk National University, Jeonju, 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 up to Si and C-terminated SiC intermediate layers on Si(111) substrates using low pressure metalorganic vapor deposition. LPCVD. The SiC intermediate layer was grown by chemical vapor deposition (CVI) using tetramethylmethylene (TMS) as the single source precursor. The Si terminated SiC surface was obtained by immediately flow of SiH4 gas after growth of SiC film. LPCVD growth of GaN on the SiC/Si(111) was carried out with a trichlorovisylmagnesium (MgCP2) and ammonia. 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 for the GaN(0002) on SiC/Si(111) was 800 arcsec. PL near band edge peak position at room temperature and FWHM were 3.37 eV and 79.25 meV, respectively. The yellow luminescence does not appear.

W3.25
INFLUENCE OF THE BUFFER LAYER COMPOSITION ON STRUCTURAL AND OPTICAL PROPERTIES OF GaN THIN FILMS ON SILICON SUBSTRATE. I. Czekalski, E. Bunkiewicz, D. Starowicz, and AdamSki, Czeslawski, Roman, and Karol, Laboratory, SWEC, University of Houston, Houston, TX, Irene Baksanov, Texas Center for 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 opto-electronic devices. The influence of the initial nucleation, buffer layer composition and growth conditions is critical for GaN epilayer properties, but is not yet fully understood. In our studies, the 2-3 μm thick GaN films and InGaN/GaN quantum well structures have been grown by MBE from a p-source molecular beam epitaxy on Si (111) wafers. Various buffer layers [AIN, SiN, GaN, and others] have been utilized in order to accommodate the 17% lattice mismatch between GaN and Si. Resulting films were studied by transmission electron microscopy, X-ray diffraction, photoluminescence, and XPS. All used buffer layers resulted in single-crystal GaN films with strong 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 AIN 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 data have shown that interdiffusion of GaN (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 3μm thick GaN layers.

W3.30
OPTICAL PROPERTIES OF MANGANESE DOPED AMORPHOUS AND CRYSTALLINE ALUMINUM NITRIDE FILMS. Meghan L. Caldwel, Ronald C. Tucceri, Hugh H. Richardson, Ohio University, Dept. of Chemistry and Biochemistry, Athens, OH; Wojciech M. Jadwiezinski, Henryk J. Lopzykowski, Ohio University, Dept. of Computer Science and Electrical Engineering, Athens, OH.

An aluminum nitride (AIN) film deposited on silicon (100) was used as the substrate for growing manganese (Mn) doped AIN film by metalorganic chemical vapor deposition (MOCVD). Growth of Mn doped AIN under layer of AIN was grown at 615°C at a pressure of 10^-4 Torr. The (6H) top layer of Mn-AIN 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, secondary ion mass spectroscopy, photoluminescence, and atomic force microscopy. The IR reflectance spectra showed a weak peak (A') at 1.0 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 33.42, 38, and 38 degrees corresponding to 100, 002, and 101 lattice planes respectively. Cathodoluminescence and photoluminescence results under the step results show that AlN is 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 GaN films have been grown using ultrasonic assisted reaction. The average alloy composition of the AlN:GaN superlattices has been observed to be strongly affected by both the substrate temperature and the ratio of flux during growth. More than an order-of-magnitude decrease in the average alloy composition is observed in the temperature range 590–670°C for a fixed V/III flux ratio. 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 identification of the processes leading to the reduction of incorporated In due to segregation and absorption. Implications of this work for controlling In segregation and description in the growth of devices will be presented.

W3.28
DEPENDENCE OF IMPURITIES INCORPORATION ON POLAR DIRECTION OF GaN GROWTH ON C-PLANE SAPPHIRE
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We have investigated the polarity of GaN films by combined impact-ionization spectroscopy and electron microscopy (CALS). It was verified that there is an orientation dependence of the Fermi level pinning by the polarity of an interface at GaN epilayer growth [1]. In this study, we report that the more impurities, including a-type dopants, are incorporated in N-based GaN (i.e. polarity) films and that the polarity is critical not only to the growth mode but also to the properties of the GaN films. Prior to the experiments, we predicted theoretically that both polarity (+c or -c) of GaN would contain more impurities using ab initio molecular dynamics. GaN films with 1.2 μm of thickness were deposited on c-plane sapphire substrates with and without the nitridation by an atmospheric two-step MOVCD method. Zinc-doped GaN films were also deposited simultaneously on both HYPE (+c) and MBE (+c) GaN substrates by hot-wire epitaxial method. Both positive and negative impurities in GaN epilayers were analyzed by secondary ion mass spectroscopy (SIMS). We calculated the adhesion energy of Ga, Mg, and Zn on the nitrogen-terminated surfaces with +c and -c polarity. This calculation predicted that the more p-dopants were inserted into the +c derived adhesion 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 MOVCD GaN films, the oxygen was detected more by two magnitude in +c GaN as Helmetman et al. reported [2]. Furthermore, the carbon, which probably came from TMGa source gas, existed at higher level by one magnitude in -c GaN. Higher level of impurities in -c GaN film is 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 galium face polarity in RF assisted MBE growth [3]. In this study, we investigated the influence of carbon content on the growth of MOVCD GaN films by MBE using an EPI Uni+NB nitride 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) of the GaN/AlN down to 5 Ångstrom steps across the GaN/AlN/nitride interfaces reveals the presence of oxygen in the AlN buffer layer. The ratio of oxygen to nitrogen in this 150 Ångstrom buffer layer is a maximum of approximately 25% of the nitrogen to oxygen ratio above the AlN buffer layer, but this decreases over the thickness of the buffer layer and reaches zero at the GaN/AlN interface. It is unclear why the oxygen ratio is lower than the AlN. Brown reports that the oxygen has diffused into the buffer region from the sapphire substrate forming this AlN buffer. Bright Field TEM reveals a crystalllographically sharp interface, while the PEELS reveals a chemically diffused interface.

W3.32 HIGH TEMPERATURE LIMITATIONS OF GaN GROWTH BY RF-PLASMA ASSISTED MOLECULAR BEAM EPITAXY DUE TO ACTIVITY NITROGEN SPECIES T.H. Myers, A.J. Pik, 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 report on the relative reactivity of the various active nitrogen species produced by thermal sources: low and high energy ions, atoms, and metastables. Reactivity is determined based on low temperature (~400°C) nitridation rates for GaN. Studies of growth rates as a function of temperature suggest the GaN surface is prone to attack by neutral and ionic nitrogen above 700°C, promoting decomposition. This leads directly to the observed lower than expected temperature for significant decreased growth rates, while this is not observed in 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 N00014-96-1-0108 and monitored by Colin E. C. Wood.

W3.33 FORMATION OF BN AND AII N DURING NITRICATION OF SAPPHIRE USING RF PLASMA NITROGEN SOURCES A.J. Pik and T.H. Myer, 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 III-nitrides. We present results that indicate B incorporation in GaN can be enhanced via operation of at least two plasma sources, the Oxford Applied Research CARS-25 and EFI Vacuum Products, Inc. Unilab. While the B can be at a relatively low level during nitride growth, Auger and XPS measurements of the surface concentration of the deuterated nitrogen indicate B incorporation occurs during the 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 the formation of a BN layer. A model that may explain one of the origin of the formation of cubic inclinations in MBE buffer layers will be presented. This work was supported by ONR Grant N00014-96-1-0108 and monitored by Colin E. C. Wood.


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 dopant elements and their concentrations. We are growing GaN by MBE on sapphire substrates, using a polycrystalline GaN buffer layer to reduce the misfit strain, thereby 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 the mobility and structural quality of the semiconductor. Optical characterization showed that the ratio of the donor band exciton (DBE) peak (3.27eV) in the photoluminescence spectrum, measured at 10K, increased with decreasing defect density. The unwanted structural peak can be suppressed by changing the diffusion of the nitrogen and using a slow acceptor transition, which is clearly related to the structural defects in GaN. By increasing the buffer layer thickness and annealing time the structural quality, mobility and photoluminescence improves in GaN epilayers. Some of these structural defects is being investigated by dark field and high resolution TEM. The effect on the electrical and optical behaviour of GaN is being assessed by determining the local change in the dielectric function of the material using optical absorption measurements. This is achieved by obtaining the low loss region (<500eV) 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 Kramer-Kronig relations.

W3.35 MBE GROWTH OF GaN FILMS IN PRESENCE OF SURFACTANTS THE EFFECT OF Mg AND Si, Guido Milla, INFN and Dipartimento di Fisica, Univ. Cagliari, Cagliari, ITALY; A. Adleman, B. Brandin, CEA/Grenoble, IRPh/NS/P2M, Grenoble, FRANCE; P. Peylin, Univ. J. Fourier, Lab. de Physique et Modélisation des Milieux Condensés, 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 GaN and N growth. 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 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 1/100th of the Ga flux. A deep hollow in the growth rate of GaN as a function of the Mg or Si 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 sharp 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 AI IN PLASMA-ASSISTED MBE GROWN GaN Gershenzon, O. Zebiri, J. V. Thordarson, Q. S. Dinh, G. Ste Changing, T.G. Andersen, 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 have 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 1.5A. 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 V/cm. Photoluminescence gave one peak attributed to the neutral donor-bandgap transition 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 CHARACTERISTICS OF GaN GROWN BY ECR-MBE USING HYDROGEN-NITROGEN MIXED GASES, A. Pic, J. J. V. Thordarson, Q. S. Dinh, G. Ste Changing, T.G. Andersen, Department of Microelectronics and Nanoscience, Chalmers University of Technology and Göteborg University, Göteborg, SWEDEN.
We have demonstrated GaN growth by electron-cyclotron-resonance plasma-excited molecular beam epitaxy (ECR-MBE) using hydrogen-nitrogen plasma (H-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 (SEM). 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 single nitrogen plasma (N$_2$ plasma) and H-N$_2$ plasma. It was found that the remarkable change in surface morphology appeared by addition of H$_2$ to N$_2$ plasma. Although some pits were observed, the coherence of GaN layers using N$_2$ plasma was better than that of H-N$_2$ plasma. In contrast, hexagonal column-like structure was mainly observed in the GaN layers using H-N$_2$ plasma. TEM results showed that the surface of GaN using H-N$_2$ plasma formed [1111] facet. It is considered that facet formation is promoted by addition of H$_2$ to N$_2$ plasma. It is shown that the surface morphology of GaN using H-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-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$_x$ related excited species in the H-N$_2$ plasma.

W3.38
DEPOSITION OF ZINC-BLENDENE ALGON WAFERS ON SI(100) AND MgO(100) SUBSTRATES

AIN 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 zincblende phase of AlN. To date very little is known about the physical, electrical, and optical properties of zincblende 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 zincblende structure on Si(100) and MgO(100) substrates. The films were deposited by Plasma Source Molecular Beam Epitaxy (PSMBE). Zincblende 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 zincblende AlN (200) and (400) reflections. Using the XRD data the lattice parameter of zincblende AlN was calculated to be 3.199 Å. Transmission 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 MOVCD ON GaAs(100), Da-feng Xu, Hui Yang, De-geng Zhao, Shan-feng Li, Hsing-lan Wei, National Research Center for Optoelectronics Technology, Institute of Semiconductors, Chinese Academy of Sciences, Beijing, CHINA.

Cubic GaN:Mg samples grown by MOVCD 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 decrease in ammonia flow 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 peak location of GaN decreased, while the blue Mg-related emission increased. Beside a shallow acceptor level at 0.21 eV, additional three Mg-related deep levels were found around 215 meV, 334 meV, and 570 meV from the conduction band. However, the Mg concentration was too low, the Mg-related efficiency decreased. This may be attributed to the increasing of nonradiative center under high Mg doping.

W3.40
ELECTRICAL PROPERTIES OF MOVCD-GROWN ZINC-BLENDENE InN AND GaN COMPOUND SEMICONDUCTORS, J.R.L. Fernandez, A. Tabata, J.R. Loin, A.P. Lima, Instituto de Fisica da Universidade de Sao Paulo, Sao Paulo, Brazil, V.A. Chibis, Universidade de Sao Paulo, Brasil, V.A. Chibis, Universidade de Sao Paulo, Brasil, E. Alfermos, Instituto Nacional de Pesquisas Espacais, Sao Jose dos Campos, BRAZIL; D.J. As, D. Schikorski, K. Lischke, 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 infra-red [2]. The growth in this work was focused in the cubic GaN and GaN compounds grown by MOVCD 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 on the temperature interval 4 to 300 K. The Hall effect of the 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. The doped sample 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. Orion and C.T. Foxon, Rep. Prog. Phys. 61, 1 (1998).

W3.41
ARSENIC EFFECT FOR HEXAGONAL GROWTH SUPPRESSION ON A CUBIC GaN GROWTH USING METAL-ORGANIC CHEMICAL VAPOR DEPOSITION, S. Yoshida, T. Kimura, J. Wu, K. Itoh, Department of Univeristy of Tokyo, Bunkyo-ku, Tokyo, JAPAN, and Y. Shiraishi, Research Center for Advanced Science and Technology, The University of Tokyo, Meguro-ku, Tokyo, JAPAN.

Such III-V materials such as GaN and GaNP are very promising for light-emitting devices over a wider range of wavelength due to having a wide bandgap. Recently, it has been reported that InGaN-GaN QD, QW, and QDs structures have been grown on GaN substrates by gas-source molecular beam epitaxy. However, there is a serious problem involving the difference in the crystal structure of GaN (wurtzite) and GaAs (zincblende), resulting in a growth-difficulty of this alloy. There have been no reports concerning the growth of InN-rich cubic GaN (InN-GaN) and GaNP (InN-GaP). We report on As-suppression effects of hexagonal GaN in a c-GaN epitaxial layer and the characterization of the GaN films grown by metalorganic chemical-vapor deposition (MOVCD). A thin buffer layer (20 nm) was first grown on a substrate at 580°C using trimethylgallium and dimethylhydride (DMHy), and GaN samples were grown at different AsH$_3$ flow rates (0~450 μmol/min) at 925°C. As a result, three types of surface morphologies were obtained: the first was obtained as a smooth surface (AsH$_3$ = 0 μmol/min); the second was a mirror-like surface having small and isotropic grains (45 μmol/min < AsH$_3$ <= 225 μmol/min) and the third was a three-dimensional surface morphology (AsH$_3$ > 50 μmol/min). Furthermore, it was confirmed using X-ray diffraction that the mixing ratio of hexagonal GaN in cubic GaN decreased with an increase of AsH$_3$ flow rate. We could obtain a GaN alloy having a cubic component above 85% at AsH$_3$ flow rates above 100 μmol/min. Therefore, the MOVCD growth method using AsH$_3$ and DMHy was effective for suppressing hexagonal GaN.

W3.42
SYNTHESIS OF (InGaN)(AlN) ALLOYS BY ION IMPLANTATION, S. Clarke, S. Glisson, and R. Goldman, Department of Materials Science and Engineering, V.H. Rothberg and B. Mech, Department of Nuclear Engineering and Radiological Science, Roy Clarke, Department of Physics University of Michigan, Ann Arbor, MI.

Mixed-using nitride-recentide 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. We present new results on InGaN/AlN alloy synthesis by ion implantation into GaAs, InAs, and InGaN-based heterostructures. Using a variety of implantation and rapid thermal annealing conditions, we have been able to obtain several different nitride-recentide phases. Compositional analysis confirms that significant nitrogen incorporation into the samples. Using four-circle x-ray diffraction with a rotating sample mode, we have found evidence of coexisting cubic and hexagonal phases of GaN implanted and annealed GaAs. The cubic to hexagonal ratio in composition from 77 to 88% N and are oriented 9° away from the GaN 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 InGaN alloys will be discussed. Microstructural and optical studies by transmission electron microscopy and photoemission will also be presented.


W3.43
METAL-ORGANIC VAPOR PHASE EPITAXY (MOVPE) OF GaN/ GaN QUANTUM WELLS USING TERTIARYBUTYLHYDRAZINE
Torsten Schmidtting, 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 GaN, this can be achieved for GaN-based devices by heteroepitaxy with nitrogen. However, carrier recombination rates beyond a few percent have been difficult to obtain in MOVPE at the high temperatures necessary for the decomposition of the used N-source. Progress has recently been reported by several authors using dimethylhydrazine (DMH) which has a low decomposition temperature of 450°C. Tertiarybutylhydrazine (TBH) has an even lower decomposition temperature of 300°C [U. W. Pohl et al., Mat. Sci.Engin. B 50 (1999) 30] 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 DMH has also been reported for GaN epilayers grown with TBH [U. W. Pohl et al., Jpn. J. Appl. Phys. 38 (1999) L107]. We have grown high-quality strained GaN/GaN quantum wells under various growth conditions using both tertiarybutylhydrazine (TBH) or ammonia as N precursors. The good structural quality of the samples was proven by X-ray diffraction. The growth mechanism of nitrogen incorporation with decreasing growth temperature, similar to the growth with DMH. At low partial pressure of TBH, the effect of using either TBH or ammonia as nitrogen precursor on the nitrogen content is found to be small. A high nitrogen content of about 15% was achieved using TBH at a comparably high nitrogen partial pressure ratio of TBH/(TiH4+TBH) near 0.9 and low growth temperatures of typically 530°C. The photoluminescence intensity decreases with increasing nitrogen content but recovers after annealing. The annealing microstructure of thick, partially relaxed GaN layers provides clear indication that the use of TBH, 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

In recent years, the technical application of GaAs/GaAs systems as laser emitting systems has attracted much attention. Still many problems concerning grown-in defects, lifetime, and thermal stability remain. This inspired us to undertake the present investigations on GaAs/GaAs/GaAs heterostructures, which were grown on GaAs wafers by solid-source molecular beam epitaxy and Zn excitation by an rf plasma source. Maximum N concentrations in the N-enriched layer where kept in the range between 10^15 cm^-2 and 10^18 cm^-2 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 second-derivative infrared absorption spectroscopy (S-IRAS). Microstructural observations of the N peaks was numerically simulated with the program package ZOEMIE. The markedly non-Gaussian shape of the N distribution after thermal annealing can be excellently described within the framework of a diffusion limited mechanism, which involves As interstitials (Ia). N atoms substitutionally incorporated on the As sublattice (N) and interstitially dissolved N atoms (N). For the first time data concerning N diffusion and As diffusion were obtained.

W3.45
IN SITU MONITORING OF GaN METAL-ORGANIC VAPOR PHASE EPITAXY BY SPECTROSCOPIC ELLIPSOMETRY IN THE DEEP UV

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 GaN on basal plane sapphire we attached a deep-UV MOVPE reactor. Both, ammonia (NH) and tertiarybutylhydrazine (TBH) were used as nitrogen precursors. For reference purpose the dielectric function of hexagonal device grade GaN was measured between RT and 100°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 epilayer. Nitridation was found to start at about 100°C and results in an approximately 2 nm thick AlN layer formed on top of the substrate. An optimized buffer layer thickness of 25 nm was determined from the in situ spectra. The kinetics of the transformation from the amorphous to the 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 grown epilayers.

W3.46

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 but recovers (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/SC (0001) GROWN AT VARIOUS TEMPERATURES BY MBE

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 characterization 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 density of the film 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 precipitation of spiral growth modes decreases with increasing substrate temperature. Spiral growth modes are known to arise from screw dislocations emerging at the film surface. Basal plane stacking faults can lead to the generation of double- and single-hairpin boundaries (PHB'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 arcminutes for all of the films we examined. The double crystal rocking curves and the triple crystal diffraction patterns show 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 differences seen in the TEM images and how the defect morphology are related to the growth temperature.

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 spots, which increases with increasing injection conditions and also with decreasing temperature of the measurement. CL measurements on thick samples suggest a meandering path 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. We present measurements by electron holography of the strain induced field around the dislocation, and discuss these fields with respect to gettering of the intrinsic atomic defects.


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 (11-20) 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 show that a mixed ionic and covalent model for the dislocation core, with selfconsistent potentials, indicates 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 sample reveals that the core contains 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, Jinming Zhu, Bo Shen, Ren Zhang, Yuanzheng Zhou, Peng Chen, Weiping Li, Wenjun Liu, Zhenlin Yang, Youxian Zheng and Shaojung 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). GaN epilayers were grown on sapphire buffer layers. Corresponding to the density of threading dislocation (TD) increasing about one order, the yellow luminescence (YL) intensity was strengthened from negligible to two orders higher than the high-quality layer. The full width at 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 microscopy (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 ANNELING ON THE DENSITY OF DISLOCATIONS IN HETEROEPTAXIAL GaN LAYERS. Dzmitry Kolesnik, Witold Lesyk, Jan Jurczyk, Institute of Physics, Warsaw, POLAND; Piotr Bluzewski, Institute of Physics, Polish Academy of Sciences, Warsaw, POLAND.

Heteroepitaxial layers of GaN on sapphire have been annealed at temperatures up to 1600K 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 and time. It was found that the density of dislocations increases when the temperature is above 1530K. Observations of cross sections of the samples have shown that the density of dislocations parallel to the surface decreases considerably. Plan view observations revealed ordering of the dislocations. The above results show 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, Kwonju Institute of Science and Technology, Dept. of Materials Science and Engineering and Center for Electronic Materials Research, Kwanju, KOREA.

The evolution of lattice structure of GaN nucleation layers during the initial growth process of MOCVD was investigated by x-ray scattering measurements. The nucleation layer grown at low temperature of 500°C was predominantly cubic GaN with the lattice constant a=4.08 Å. As the film was annealed to 1100°C, the cubic GaN transformed into hexagonal GaN with decreased GaN atomic layer spacing (=5.18 Å, as=4.18 Å). Both the as-grown and the annealed nucleation layer contain small amount of extremely well aligned domains that are tensile strained. The in-plane 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 ORTHOGONAL DETERMINATION OF THE COMPOSITION AND ELASTIC STRAIN IN InGaN AND AlGaN LAYERS. A. Vantinne, M.F. Wu, S. Hogg, G. Langouche, Institut 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, 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 bonding of the epilayer. Since these parameters are not always well known, either shows 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 ions, 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 crystalinity 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 to normalize the sapphire backscattering parameter to 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 stress while the AlGaN layer is under tensile stress. The strain is influenced both to full film direction. The results will be compared to strain data for GaN layers.
W3.54 STRUCTURAL ANALYSIS OF (GaN)N[As]/GaN MQW STRUCTURES GROWN BY MOVPE. C. Giannini, L. Tagger, Pastris-CNRSM, Brindisi, ITALY; F. Hohrad, J. Koö, W. Seidel, Materials Science Center, Philips-University, Marburg, GERMANY.

(GaN)N alloys grown on GaN 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 having potential for telecommunication applications. Here, we report on the structural characterization of (GaN)N material system and the surface morphology of the MQW system under thermodynamic equilibrium conditions. Therefore, extreme non-equilibrium conditions at low growth temperatures are required in order to maintain homogeneous epitaxial deposition for the stable (GaN)N material system. In this work, we investigate the structural properties of (GaN)N epilayer layers and (GaN)N/GaN MQW grown at temperature by metalorganic vapor phase epitaxy (MOVPE) using triethylgallium (TEGa), tristrimethylsilylamine (TMSA), and ammonia as precursors, 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 (GaN)[N] 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 GaN 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 4th order indicate a good interface quality. However, peak broadening and diffuse scattering in RSM, observed for samples with N-contents larger than 4%, can be attributed to an inferior quality of the epitaxial layer. These x-ray diffraction evidences can be explained by assuming a mosaic structure of the epilayer layers, probably caused by clustering phenomena.


The active layers of GaN grown on SiC or sapphire contain high densities of threading dislocations. Using high resolution electron microscopy, misorientic 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 cores. The first two configurations were observed at a similar frequency for different locations and at single boundaries. The 4/6 ring structure was found to be in high angle grain boundaries. Energetic calculations show that these three configurations have similar formation energies in GaN, which probably explains their observation. The formation of [1010] stacking faults, which can be formed in the wurtzite [Ga,A1,In], 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> (1-2110) 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> (1-2110) atomic configuration in GaN layers. The 1/6<20-25> configuration was found in small regions inside the AlN-InN layer in cross-section observations. This folds rapidly to the basal plane, and when back into the prismatic plane, it bears the 1/2<10-11> (1-2110) atomic configuration.

W3.56 THREADING DISLOCATION DENSITY REDUCTION IN GaN/SAPPHIRE HETEROSTRUCTURES. A.K Sharma, A. Kesh, and J. Naranjan, 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 α-Al₂O₃ (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 present threading dislocation densities 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]<c><c><c>/0001> or [0001]<c><c><c>/10<11>, which is equivalent to a 30° rotation in the (0001) plane. This film contained a high density of stacking faults with average spacing 15 nm terminated by partial dislocations. The density of partial dislocations was estimated from cross-sectional TEM to be 7 x 10⁹ 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 the film surface, are also visible. The concentration of threading dislocation is relatively low (~2 x 10⁵ cm⁻²), compared to misfit dislocations. The average distance between misfit dislocations was found to be 22 Å. Contrast modulations due to the inherent new misfit dislocations are seen on high-resolution cross-sectional TEM micrograph of GaN/α-Al₂O₃ 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.

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Two GaN films with a thickness of 3 microns and 20 microns were grown by HVPE on sapphire and 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 microns GaN/sapphire film was found to be featureless, while the surface of the 20-micron GaN/sapphire sample showed the presence of crescent-like growth. Combination of MCL spectra measurements and of MCL and EBIC imaging of such growth regions allowed 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/Aperture films show the presence of mosaic to two-dimensional EBIC which is not related to any morphological features. The diffusion length measurements on these samples give the values of 33 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 bandage (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 10⁶ 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. L. Zhou, F. Phillip, Max-Planck-Institut für 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 1/2<1120>, 1/2<1123>, and [0001] are typical line defects, predominantly the first type of dislocations. Their densities are typically 1.5 x 10¹⁴ cm⁻² and 4 x 10¹⁰ cm⁻² on SiC and sapphire, respectively. Additionally, planar defects characterized as inversion domain boundaries lying on [1010] planes have been observed in GaN films on sapphire substrates. Inversion domain density is 4 x 10¹⁰ cm⁻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 ID-II with Ga-N bonds across the boundary was deduced. High resolution transmission electron microscopy observations and the corresponding simulations confirmed the ID-II structure determined by the analysis of displacement fringes.

W3.59 INVESTIGATIONS OF In,Ga,GaN MULTIGROWTH WELLS STRUCTURES BY GRAZING INCIDENCE X-RAY DIFFRACTION AND REFLECTIVITY TECHNIQUES. Jürgen Blasing, Ales Krost, Otto-von-Guericke University, Institute of Experimental Physics, Magdeburg, GERMANY; Michael Heukel, AIXTRON A.G, Aschheim, GERMANY.
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/cmK. This compares with the value of 1.30 W/cmK reported for bulk single crystal material at room temperature and the same value we measured for a HVPE thick film grown on sapphire with a 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.

W3.03

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 samples studied. All samples were characterized by XRD, BET, particle size analysis, and combustion analysis and showed deviation from ideal stoichiometric composition with varying quantities of O impurity. As N is the major component of GaN and causes the large exothermic heat of oxidation in our thermochemical cycle, we plot the calorimetric data in kJ/g against the N content of the samples and linear fit to the data and then gives the heats of combustion for stoichiometric GaN to determine the heat of formation through a thermochemical cycle. The same methodology was used previously to study SiN₂ 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.

W3.04

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 H₂, N₂, and vacuum environments, few studies have focused on GaN decomposition in mixed NH₃ and H₂ flows. This is of more importance for the MOVPE growth environment. In this presentation, GaN decomposition is measured in mixed H₂ and NH₃ flows. At 1000°C, the GaN decomposition rate is reduced from approximately 1 x 10⁻⁶ cm³ s⁻¹ to pure H₂ to a minimum of approximately 2 x 10⁻⁷ cm³ s⁻¹ in pure NH₃. NH₃ is added to the total flow. As the NH₃ density is increased above 1 x 10⁻⁹ cm⁻³ s⁻¹ the GaN decomposition rate increases. The increase in the decomposition rate as the NH₃ density increases may partly explain decreases in the GaN growth rate in the NH₃ growth region. This increase in the NH₃ decomposition rate as the NH₃ density increases may partly explain decreases in the GaN growth rate in the NH₃ growth region. This increase in the NH₃ decomposition rate as the NH₃ density increases may partly explain decreases in the GaN growth rate in the NH₃ growth region.

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W3.05
EXPOSURE OF THE WURZITE GaN LUMINITE (0001) SURFACE TO MAGNESIUM AND ARSENIC. Y. Ramaschandran, R.M. Feinstra, Department of Physics, Carnegie Mellon University, Pittsburgh, PA; D.W. Greve, Department of Computer Engineering, Carnegie Mellon University, Pittsburgh, PA; A.R. Smith, Department of Physics and Astronomy, Ohio University, Athens, OH; W.L. Surley, L.M. Salminen-Riba, Department of Materials and Nuclear Engineering, University of California, Berkeley, CO; J.E. Northrup, Xerox, Palo Alto Research Center, Palo Alto, CA.

We have studied the exposure of the wurzite GaN (0001) surface to As and Mg in order to determine the effect of 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 GaN-poor growth regime. In the absence of Mg, GaN growth in the Ga-rich 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, shows the presence of a single peak at the surface 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 incorporating Mg atoms in a plane. Ammonium surface during growth does not have much effect on the RHEED patterns which remain dim and streaky. However, the GaN layer is not uniform and the RHEED patterns approach the boundary between Ga-rich and Ga-poor, a bright 2x2 RHEED pattern is seen during growth which persists upon cooling the sample. We have seen the 2x2 reconstruction of the [0001] plane in each nitrogen-rich growth conditions which suggests a surface state of As. Under very Ga-rich growth conditions, the surface roughens as before. We verify this behavior of As on Ga-polar GaN for different Ga and As concentrations and discuss theoretical results for the reconstruction of the surface. 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. Crugeul, Y. Yang, G.J. Lepere, 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 surface morphology at the atomic scale is the understanding of adsorption. 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 information on the electrostatic and electronic field generated by an electron at the work function and electron density and emission direction. The effects can be inverted by using the holographic principle to obtain real space images 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 T4 site with one N atom directly below it. Also the image demonstrates that there is one monolayer Ga adsorbs on the surface. The Ga adsorbs sit on the so-called H4 site with no atom directly below it. The site position results are rather complex. As a result theoretical calculations were performed and verified the assignment of the peaks in the experimental image. Research supported by ONR DEPScCOR and Wisconsin Synchrotron Radiation Center supported by NSF.

W3.67 AMMONIA ADSORPTION ON GaN(0001). H. Crugeul, Y. Yang, S.H. Xu, G.J. Lepere, Montana State University, Bozeman, MT; E. Rotenberg, Advanced Light Source, Berkeley, CA; J.F. Schetzina, North Carolina State 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 growth of GaN on (0001) GaN is well known to be associated with photoemission. The MOVPE grown samples at N.C. State University were successfully cleaned and measured at the Advanced Light Source (AL) in Berkeley. High-resolution data were collected with a focusing (B) and a non-focusing (A) photoemission mode for the clean surface and for sequential exposures of Ammonia at two different temperature (295°C and 600°C). The clean substrate emission for Nδ 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 lower binding energy. A widely accepted model is that the film has Ga polarity with a Ga adlayer. The Nδ shifted peak is attributed to the two monolayers of GaN. The Ga adlayer contains about 1.5% of Nδ exposure which correlates with the extinction of the VB surface state. This is attributed to one or two monolayers. The Nδ level shows three new components with relative shifts of 0.95, 0.78, and 0.74 eV to larger binding energy. A theoretical model to account for 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 Nδ increases. The small increase in the component is attributed to the Ammonia exposure modifying the Ga adlayer. Annealing experiments were performed and the Nδ induced effects disappear at about 1500°C, with the surface essentially returning to the clean condition, with very slight differences in the Nδ emission. The results will be discussed in terms of possible adsorption models. Supported by ONR DEPScCOR.

W3.68 IN-SITU PHOTOELECTRON SPECTROSCOPY INVESTIGATION OF THE REACTIVITY OF THE ALUMINUM NITRIDE SURFACE.

T. Wrase, P. Reinke, P. Oelhaf, Universität 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, the negative electron affinity of AlN is investigated using angle-resolved photoemission spectroscopy (ARPES). The results are interpreted in the context of the electronic structure and chemical composition of the as-prepared AlN surface. The samples were prepared by high-energy Ar+ sputtering in a UHV/Ar+ sputtering chamber, thus avoiding immediate contamination of the surface. The subsequent analysis of the samples was performed in situ and photoemission spectroscopy in the ultraviolet (UPS) and x-ray regime (XPS) is employed. Owing to the in situ preparation, it is to our knowledge the first time possible to obtain reliable information on the electronic structure and chemical composition of the as-prepared AlN surface. The results 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 the d and p type character of the valence band. We observe the electron affinity of AlN, defined as the energy difference between the Fermi level and the top of the valence band, to be 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 rapid accumulation of oxygen on 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 a passivation layer. Different results were observed for the AlN surface and their influence on the electron affinity and band bending will be compared and discussed in detail.


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 oxidation of the electronic structure of n-type GaN(0001) during the oxidation process. Angle resolved measurements were made with in situ photoemission spectroscopy (IPES), ultra violet 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.

W3.30 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 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 Omori, Yusaku Inaba, Seiichi Takami, Momoyo Kudo, Akira Miyamoto, Tohoku Univ., Dept. of Materials Chemistry, Sendai, JAPAN; Yasushi Iyeoka, Takayoshi Miura, Sumitomo Chemical Co. Ltd., Tsukuba Research Lab., Tsukuba, JAPAN.

The theoretical calculation of the growth of perfectly ordered GaN layers on sapphire substrate using the Density Functional Theory (DFT) method is now possible due to the development of the GaN or AlN buffer layers.
deposition technique. It is reported that the initial treatment of sapphire substrate, such as initial nitridation and low temperature GaN buffer layers, affects the morphology and crystalinity 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 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.


3.7.2 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 vacancy in a shallow donor, the Ga vacancy as an acceptor and the interstitials act as dopant defects. Formation energies of 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 interstitial domain boundaries. To study 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: [100] stacking mismatch boundary (SmB), [100] inversion domain boundary (IDB) and a [1120] IDB. Simulations are carried out using the GULP computer code incorporating polarization effects using the shell model. Large supercells containing over 200,000 atoms are employed in order to eliminate intercellular interactions. Calculations on the [100] 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 these two vacancy energies 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 disturbing the surrounding structure; these results are compared to those found for the [1120] IDB and the [100] SmB.

3.7.3 LATTICE LOCATIONS, DIFFUSION, AND EXTRINSIC LEVELS OF Li IN GaN. Fabio Bernardini andvincenzo Fiorentini, INFN and Dipartimento di Fisica, Università di Cagliari, ITALY.

As a first step to obtain detailed information about the interaction between Li ions and GaN lattice, density functional calculations were performed for Li incorporation into the GaN crystal. The calculated Li-ion binding energy of 0.5 eV agrees well with the experimental values [3]. In order to study the Li incorporation and diffusion in GaN, a computational model containing a Ga vacancy was created in order to create a stable Li-ion substitution. The calculated binding energy of 0.5 eV is in agreement with the experimental results.

Several Al,Ga$_{1-x}$N (x=0.30) (doped and undoped), 0.45% (doped) thin films were grown by MOCVD on 2 nm thick GaN layer using Al$_2$O$_3$ substrate. These films were used to study the active part of HFEPTs with n, μ product of about 10$^8$ (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


We investigated by first-principles density functional calculations a number of junctions of both wurtzite and zincblende GaN and AlN with several metal contacts (Ti, Cd, Au, Ti, and Ni) on zincblende (100) and wurtzite (0001 and [111]) surfaces. The technologically relevant result of this study is the theoretical valence Schottky barriers, we mention here the lowest and highest values, namely 0.1 eV for Au on w-GaN, and 2.9 eV for Ti on w-GaN. In this latter context our results indicate that the actual interface at a real-world T/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. Yusuke Inaka, Takayuki Oonou, Ryuji Mura, Seiichi Takami, Momoji Kubo, Akihiko 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 epitaxial nitrides, is large. Thus, buffer layers that are grown at low temperature (AlN, GaN) are used to obtain the epitaxial GaN layers. In this study, we investigated the initial stage of AlN and GaN growth process on Al$_2$O$_3$ (100) surface using the classical 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 energy of AlN are larger than GaN in dimer and trimer cases. Moreover, from the optimized structures it can be seen that the AlN bond is shorter and hence more covalent than the GaN bond. This result suggests that at the initial stage of growth process the AlN molecules tend to aggregate each other to form stable clusters. On the other hand, the weak GaN bond provides a possibility of forming the GaN monolayer deposition film on Al$_2$O$_3$ substrate.

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

We present a theoretical study of the vibrational properties of the (AlGaN) 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 (AlGaN) 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 recent 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 A$_2$(LO) modes are the best candidates for the material characterization of this system as they have a well defined symmetry, 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$_x$Ga$_{1-x}$N LAYERS GROWN BY MOCVD. J.I. Ho, U. Stimming, Z. Liliental-Weber, W. Swider, J. Washburn, E.O. Lawrence Berkeley Laboratory, Berkeley, CA; C. Eising, R.C. Dupuis, R.D. Dupuis, Microelectronics Research Center, University of Texas, Austin TX.

Several Al$_x$Ga$_{1-x}$N (x=30%) (doped and undoped), 45% (doped) thin films were grown by MOCVD on 2 nm thick GaN layer using Al$_2$O$_3$ substrate. These films were used to study the active part of HFEPTs with n, μ product of about 10$^8$ (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-related defects within the Al$_2$Ga$_{1-x}$N films. The reduction of these V-related defects has taken place about 20 mm above the 110N/AlN/GaN interface. The density of these V-related defects was associated with the presence of the threading dislocations propagating from the GaN/Al$_2$O$_3$ interface. We show that the density of these V-related defects increases with doping level and also with the Al mole fraction in the films. The formation mechanism of the V-related defects seems to be related to the concentration of donors (or other impurities) at the edges of the growing film. This is supported by high resolution TEM analysis. The growth front behind the V-related defects, as revealed by lower Al concentration in films with lower V-related defects, 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. Byungsoo Park, Jin-Seok Kim, Ok-Hyun Nam, Cheolsoo Sone, Bongjun Kim, Yeojun Park, Theil Kim, Photomet Labs, 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 a 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 doping AlGaN/GaN superlattices as the cladding layer in violet laser diode. Recently, Kunogi 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 composition of both the layers and the carrier 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 structure was increased as the thickness of the well and barrier was increased. Additional results will be reported at the conference.


Epitaxial GaN films deposited on 6H-SiC were implanted with 100 keV Si, 4 and 80 keV Mg, at 77 K, 823 K and 973 K of fluences ranging from 1E15 to 1E16 cm$^{-2}$. All implanted samples were annealed with 40 min of AlN films to protect GaN from degradation during high temperature annealing of implantation damage. Photoluminescence spectra of the implanted GaN with AlN capping and uncoated samples were found to have almost identical intensities, 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 gas. Optically grown, structurally characterized 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 unimplanted 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 decrease in the yellow luminescence with increase in implantation fluence and decrease in implantation fluence. The full width half maximum (FWHM) of the yellow luminescence peak decreased as a function of fluence with increase of implantation temperature. However, for a given implantation temperature a very thin layer of the yellow luminescence peak was not significant. Detailed characterization of annealed samples is underway to understand the influence of implantation fluences and temperature on dopant activation and damage annealing.

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

The identity of the shallow donor in epitaxial GaN is still under investigation. Oxygen is considered a possible candidate to explain the unintentionally doped layer of the GaN/GaN heterostructure. 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 1E18 to 1E19 cm$^{-3}$. The observed carrier concentration had a sublinear dependence on oxygen partial pressure. Photoluminescence was used to characterize the shallow donors in the doped films. In addition to free donor and acceptor bound exciton emission bands, a new broad emission band at lower Al content was observed. The 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 ME sulfides GaN:Ga Sulfides epilayers doped by Si, D. J. As, A. Richter, J. Busch, B. Scholz, M. Zilbauer, J. Münk, D. Schenk, and K. Lischka, Universitats-Paderborn, FB 6, Physik, Paderborn, GERMANY

The optical and electrical properties of n-type doping with Si in cubic GaN:Ga (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 μm/h and a layer thickness of about 1 μm, respectively. Elemental Si is evaporated from commercial available effusion cells with varying S/IXs fluxes ranging from 10$^{-6}$ to 5×11$^{-1}$ atoms/cm$^2$. Low temperature photoluminescence (PL) and temperature dependent Hall-effect measurements are used to study the optical and electrical properties. At 9 K the spectrum of the samples with the highest n-type doping level (8.510$^{14}$ cm$^{-3}$) is dominated by an excitonic transition X at 3.26 eV and an omnipresent donor-acceptor pair transition (D$^A$, A) at 3.15 eV. With increasing Si flux a clear shift of the (D$^A$, A) emission to higher energies and intensities is observed. For samples with a Si flux exceeding 1×10$^{15}$ cm$^{-2}$ the two bands 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 discussed in view of other (impurity) bands. An activation energy of 99±3 meV can be attributed to the band gap filling effect. The influence of the high doping density (1×10$^{19}$ cm$^{-3}$) on the electrical properties of c-GaN is reflected in the dependence of the electron mobility on the free carrier concentration. Similar to hexagonal GaN the mobility first increases with carrier concentration, reaches a maximum value of about 100 cm$^2$/Vs at an electron concentration of about 3×10$^{18}$ 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. Yeejun Sun, Long Seow Tan, Siew Chin Tan, National Univ of Singapore, Dept of Electrical Engineering, Center for Optoelectronics, SINGAPORE

A new annealing process was carried out on the beryllium implanted gallium nitride. The implanted samples were annealed in ambient of forming gas including 20% H$_2$ at first and then in pure N$_2$ atmosphere. The activation energy of the Be acceptor in the latter was determined 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 80±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. M. Oliis, V. Ranki, K. Sarama, P. Hautojärvi, Laboratory of Physics, Tampere University of Technology, FINLAND. J. Laitinen, Technological Research Centre of Finland, FINLAND, J. M. Kaukoranta, J. Vahakangas, F. Päkkö, Institute of Experimental Physics, University of Warsaw, POLAND. M. Leszczynski, I. Gregoire, UNIPRESS, High Pressure Research Center, Polish Academy of Sciences, POLAND.

Epitaxial GaN layers grown by MOVPE 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 InGaN/GaN heterostructures. Mg is known to form an interstitial Mg$_2$Ga$_2$O$_5$. Only 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 homoeophasic material, where the
dilution concentration is greatly reduced compared to layers
grown on substrates. The higher concentrations are therefore
found in n-type GaN, 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 the 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.

W3.84


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, namely 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, recently, 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
metallographic samples with co-doping 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 increasingly increased as SiH$_4$ flows increase,
and then type conversion occurs at the SiH$_4$ flow rate of 0.13
mmol/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 measurements. 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
codoped p-type GaN with Mg showed 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
corder of magnitude for Zn with Mg codoped 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$_{x}$Ga$_{1-x}$N/GaN DOPED SUPERLATTICES. L.D. Goergef and E.F. Schubert, Dept. of Electrical and Computer Engineering, Boston University, Boston, MA;

A. Ostinsky and P.E. Norris, AZ Applied Technologies, Woburn, MA.

Mg-doped superlattices consisting of uniformly doped Al$_{x}$Ga$_{1-x}$N and GaN layers are analyzed by Hall-effect measurements. Acceptor activation energy of 0.08 eV and Mg concentration of 5$	imes$10$^{-4}$ in the 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$	imes$10$^{10}$ cm$^{-3}$ and 4$	imes$10$^{10}$ cm$^{-3}$ for x = 0.10 and
0.20, respectively. The increase in hole concentration with Al content of the superlattices is consistent with theory. The room temperature
conductivity of these samples is low and activation energies in n-type samples are 0.15 eV/cm$^{-3}$ and 0.04 eV/cm$^{-3}$ for an Al mole fraction of x = 0.10 and 0.20,
respectively.

W3.86

STUDIES OF S.DOPOING OF AlN GROWTH BY PSMBE. Feng Zhong. Wayne State University, Dept. of Chemical Engineering and Materials Science, Detroit, MI; Changhe Huan, Gregory W.
Aker, Wayne State University, Dept. of Electrical and Computer Engineering, Detroit, MI.

AlN grown by Plasma Source Molecular Beam Epitaxy (PSMBE) is
usually an insulator with sheet resistivity values greater than
10$^{3}$ Ohm-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 its potential high bandgap AlN. Experimental studies of S-doping of AlN are investigated. S 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 source used in n-type samples) are used. The resistivities, carrier concentrations and mobilities of thin films are measured by four-point probe and Hall effect measurements, respectively. The impurity and doping concentration profile is characterized by
Cathodoluminescence and SEM, respectively. The effect 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 surface and optical properties of thin films grown by metalorganic chemical vapor deposition (MOCVD). The films were grown on c-axis sapphire (002) substrates. The optical properties of the films were characterized using reflectance and transmittance measurements. The structural properties of the films were characterized using x-ray diffraction and Raman spectroscopy. The results indicate that the Mg-doped ZnO films have a hexagonal wurtzite structure. The Mg-doped ZnO films exhibit a blue shift in the optical bandgap compared to undoped ZnO films. The Mg-doped ZnO films also exhibit a decrease in the room-temperature electrical resistivity compared to undoped ZnO films. The Mg-doped ZnO films are promising for applications in optoelectronic devices such as light-emitting diodes, UV lasers, and UV detectors. In this paper, we have explored the possibility of the bandgap engineering as a result of alloying with Mg for the above applications. Pulled 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 up to 30 at% which exceeds the equilibrium concentration by several orders of magnitude. High resolution microscopy of these samples 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 Mg$_2$O could be observed at high concentrations (> 30 at% of Mg) in the films by X-ray diffraction. Transmission optical spectra of these samples exhibited sharp band-edge with the bandgap at 3.3 eV for the sample containing about 30 at% Mg. These samples luminesced bright in UV with the luminescence peak widths being sharp. 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.


W3.88

NITRIDE DEVICES ON LATTICE-MATCHED ZINC OXIDE (ZnO) SUBSTRATES. Jeffrey E. Nasae, Germer, Inc., Atlanta, GA; Haid Molko, 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
cМО photodetectors. The properties that make zinc oxide attractive are: 1) zinc oxide has the same atomic space group as gallium nitride
(P6$_3$mc); 2) zinc oxide has a 2.2 nm lattice mismatch to gallium nitride
which makes it an electrically conductive substrate, and 3) zinc oxide is a 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 mismatched barrier interfaces (SBMs). 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 be 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 for use in electron devices. The electrical properties of the nitride films will also be discussed.

W3.90


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

log n, a factor of two decrease in $n$ for every decade increase in $n$. We found $n \approx 1.95 \text{ W/mm}^2 \cdot \text{K}$ for the most lightly doped sample ($2\times 10^{10}$ cm$^{-3}$), while a previously reported sample at $1.21 \times 10^{10}$ cm$^{-3}$ on LEO material [1] and $1.3 \times 10^{13}$ cm$^{-3}$ on a HVPE sample [2]. One set of samples had unintentional $n$ and thicknesses $(t)$ in the range of $0.9 \times 10^{11} \text{ cm}^{-3}$ and $5 \times 10^{-4} \text{ cm}$, respectively. For the second set, $n$ was held constant at $10^{16} \text{ cm}^{-3}$ and $30 \times 10^{18} \text{ cm}^{-3}$. Our observation also helps to explain $n$ of the LEO material, with $n \approx 2 \times 10^{12} \text{ cm}^{-3}$ [3]. $n$ is similar to that of other semiconductors in a comparable temperature range [4]. The decrease in the lattice constant of Si due to increased phonon scattering (impurities and free electrons) outweighs the increase in the electron's $n$. The implications of these findings for device applications and design will be discussed.


The Brooklyn College work was supported by the ONR and the NY State Science and Technology Foundation. The Lincoln Laboratory work was supported by the US Air Force under Air Force contract F19628-05-C-002. Opinions, interpretations, conclusions, and recommendations are those of the authors and are not necessarily endorsed by the US Air Force.

W3.50
HIGH TEMPERATURE HARDNESS OF BULK SINGLE CRYSTAL GALLIUM NITRIDE. Tsukasa Oku, Osamu Nakamura, and Katsunobu Abe, NEC Corp., Tashima, NTT, 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 growth process results in a dislocation density maximum of around 107 cm$^{-2}$. 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 1.8 GPa at room temperature and increases with increasing 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 Si. The hardness of GaN is similar 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 microscopic dislocation motion and plastic deformation. Thus, the present results imply that such microscopic dislocation motion and plastic deformation may start around 1100°C on GaN, but not on Si. This also suggests that the high temperature hardness of GaN, 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 ALGaN/GaN grown on the Ga-face of GaN has a large bandgap, large spontaneous polarization difference and piezoelectric polarization. Unpolarized structures yield a positive polarization charge of $2.5 \times 10^{15} \text{ cm}^2 \cdot \text{V}^{-1}$, the polarization-induced two-dimensional electron gas is nearly large. OMPVE and MBE are used to grow $300 \text{ A}$ of $\text{Al}_x\text{Ga}_y\text{N}$ on $1 \text{ cm}$ of GaN on either sapphire or semi-insulating SiC yielding $\sim 1 \times 10^{13} \text{ cm}^{-2}$ 2DEG with 1200-1500cm$^2$V$^{-1}$s mobilities. OMCVD grown n-type GaN, with $\sim 10^{18} \text{ cm}^{-3}$, is used to fabricate high-quality 2DEG in GaN by fabricating using $\text{Tl}/\text{Al}/\text{Tl}$ grown on $1 \times 10^{13} \text{ cm}^{-2}$ 2DEG on GaN on sapphire or semi-insulating SiC. These field-effect devices have high electron mobility and high channel resistance. The field-effect devices show a high resistivity and high electron mobility. The field-effect device shows a high electron mobility and high channel resistance. The field-effect devices show a high resistivity and high channel resistance. The field-effect devices show a high resistivity and high channel resistance.
include doped layers in the AlGaN barrier and for the GaN channel. We have investigated the effects of composition, layer thickness and intentional dopant in the electrical and optical 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 20 Å AlGaN/GaN barriers. The electron density of 8.5×10^{12} cm⁻² and mobilities of 0.140000 cm²/Vs were measured at room temperature in undoped heterostructures with Al compositions greater than 20%. Intentional Si doping of the AlGaN/n-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 (45% to 1190 cm²/Vs) was observed when intentional % dopants were added to the structure. The reduction in mobility was independent of the level of Si doping (5.17 to 5.618 cm²/Vs) or the thickness (30 to 100 Å) 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, CEEMF and ECSIE, Renesas Polytechnic Institute, Troy, NY; MA. 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 10^{12} cm⁻² and the Hall mobility was 1,000 cm²/Vs. The HEMTs had threshold voltage close to zero and could operate at high positive gate bias up to 35.5 Volts, with a very low gate leakage current. NDC was observed at the gate biases larger than 1.5V and at the drain biases between 0.5V 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 mobilar 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] R. Gaska, M.S. Shur, A.D. Bychkovski, 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 INDUCED BASE TRANSISTOR. Alexei D. Bychkovski, Michael S. Shur, Department of ECE, Renesas Polytechnic Institute, Troy, NY; Remis Gaskau, Sensor Electronic Technology, Inc., Troy, NY; Ma. 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/GaN-heterostructure-based mesa AlGaN/GaN HEMTs. Typically, the use of two-dimensional electron gas induced into base by the piezoelectric and pyroelectric charges and by grading the emitter layer. Our analysis is 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 for 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 mole 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 the AlGaN-GaN/GaN HEMTs are a potential competitor to a GaN-based HBT.

11:00 AM W4.7
TWO-DIMENSIONAL ELECTRON GAS TRANSPORT PROPERTIES IN AlGaN/GaN AlGaN DOUBLE-HETEROSTRUCUTRE FIELD EFFECT TRANSISTORS. Narutaka Mochi, Tadashi Satochi, Kotto Tsuchi, Toshiyuki Nishida, Norio 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/GaN 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 SL, GaN DH, and InGaN (In=0.06) DH-FET samples were grown by metalorganic vapor-phase epitaxy (MOVPE) on SiC substrates using InN buffer layers. The AlGaN (Al=15%) barrier layer on the surface-side (300 Å) was uniformly doped with Si for supplying carriers. The thickness of the DH channel was 20 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 cm²/Vs (for a 2DEG density of 6.5×10^{12} cm⁻²), which was almost twice as large as the mobility in the GaN SL-FET sample. At room temperature, the 2DEG mobilities in the GaN DH-FET and SL-FET samples were 8.2×10^{12} cm²/Vs and 710 cm²/Vs (9.4×10^{12} cm²/Vs), respectively. The observed 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-μm-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 enhanced conduction-band discontinuity. At 300 K, a high 2DEG mobility of 850 cm²/Vs was obtained for a very high 2DEG density of 1.9×10^{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 SL-FETs.

11:15 AM W4.8
HIGH TEMPERATURE RELIABILITY OF GaN ELECTRONIC DEVICES. Takashi Yoshida and Masayuki Nakamura, NEC Laboratories, The Furukawa Electric Co., Ltd., Yokohama, JAPAN.

II-VI nitrides are very promising for electronic devices that can operate under high-temperature, high-power, and high-frequency applications, 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 wafers grown using gas-source molecular beam epitaxy (MBE). A GaN buffer layer was formed on the sapphire substrate using dimethyldihydrido (DMHD) and Ga. A thick undoped GaN layer was also grown on the GaN buffer layer using Ga and ammonia (NH₃) as a nitrogen gas source at 850°C to obtain a high-quality GaN active layer. The mobility of undoped GaN was 3500 cm²/Vsec and the carrier concentration was 6×10^{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 500h. The BJT performance did not degrade at 300°C. The current gain was about 10. The BJT performance at 500°C did not change. 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 degrade even at 400°C for 500h. The calculation of the metal-semiconductor interface was observed by secondary ion mass spectrometry (SIMS) and transmission electron microscopy (TEM).

11:30 AM W4.9

Junction field effect transistors (JFETs) 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. A maximum current density of 80 mA/mm² was obtained with a maximum 1/V of 270 mA/mm. The microwave measurement showed an f of 6 GHz and an fmax of 12 GHz. Both the drain current and the extrinsic conductance were found to decrease with increasing temperature, which is 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.
SESSION W5. ELECTRONIC AND STRUCTURAL CHARACTERIZATION

Chair: Michael S. Shan
Tuesday Afternoon, November 30, 1999
Room 302 (H)

1:30 P.M. #W5.1 POLARIZATION EFFECTS AND NANOSCALE ELECTRONIC PROPERTIES IN NITRIDE SEMICONDUCTOR HETEROSTRUCTURES. L.T. Ho, N.G. Smith, X. Ding, 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 design, engineering and the fabrication 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 we have used a variety of characterization tools, such as scanning capacitance microscopy, to study and understand the local electronic properties in nitride heterostructures. We will also discuss recent evidence for the existence of a wide range of electronic properties in nitride heterostructures.

2:00 P.M. #W5.2 MICROSTRUCTURE, STRAIN, AND PHASE SEPARATION IN NITRIDE DEVICE MATERIALS. L. T. Romano, Xerox Palo Alto Research Center, Palo Alto, CA.

InGaN 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 different mechanical 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 InGaN, the threading dislocations that are created during growth are formed along the (111) prism planes and the easy glide (100) 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 of other materials. Dislocations are not found to relieve strain by either bending or nucleating at the lattice mismatched interfaces formed within the device. Relaxation of tensile strain seems to proceed by cracking rather than dislocation formation. The large strains may, in fact, lead to a bulk phase separation in these alloys. In this talk, we will discuss InGaN-GaN multiple quantum well (MQW) LED structures with indium compositions up to $x = 0.33$ (determined by Rutherford backscattering). The visual optical properties were analyzed by transmission electron microscopy (TEM) and show no indication of phase separation. X-ray diffraction indicated the strain of these MQW structures is pseudomorphic, and TEM revealed no misfit dislocations along the highly strained well/barrier interface in samples with $x < 0.33$, only as $x = 0.33$, misfit dislocations were observed in isolated regions along the interface. The MQW 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 pressures (10 kbar), suppressed both voids and phase separation. After annealing, defects were found near inversion domains (IDs) in the GaN:Mg overlayer above the MQW. 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. 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 crack formation is 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 of the order of 500 V/cm are clearly observed. It has also been found that the stress results from 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 P.M. #W5.3 ATOMIC STRUCTURE OF EXTENDED DEFECTS IN GaN. Peter Dittrich, Valerie Potin and Gerard Niset, Laboratoire d'Etudes et de Recherches sur les Materiaux, UPRAS CNRS 6004, IMSRA, Cen. FRANCE.

The lattice parameters of wurtzite GaN layers contain large densities of extended crystallographic defects. These include edge dislocations, stacking faults, and inversion domains. The latter two are consequence of the transition from a 2H structure to a 1T' structure. The former are consequence of the transition from a 1H structure to a 1T structure. In order to understand the geometric relations between the two structures, we have studied by HRTEM 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 faults have been observed in (GaN-Al) N layers; they are relaxed by a 1/6c (10 10 10). The two types of stacking fault, they appear on coalescence of two adjacent layers related by the 11 stacking fault. In our investigations of the [1010] inversion domains, it was shown that they only form in GaN layers grown on [001] and [011] substrates. A configuration could be found that was observed for these domains boundaries, as well as another in which no N-N or Ga-N bonds occur inside the boundary, the two...
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. The thermal expansion of different GaN samples is studied by high-resolution X-ray diffraction within the temperature range of 10 to 680 K. GaN bulk crystals, a homoeptaxial layer and other 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 temperature independent, which has to be taken into account when estimating the thermal strain of GaN layers in optical experiments commonly performed at low temperatures. The homoeptaxial layer and the underlying GaN substrate with a lattice mismatch of $\sim 4 \times 10^{-4}$ showed identical thermal expansion. Comparing the lattice constants of the homoeptaxial 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. DenBraas (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

Successive growth of thick GaN layers separated by either LT-GaN or LT-AlN layer has been investigated by transmission electron microscopy and other 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 types 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

Especially for the use in laser diodes and high-temperature, high-power electronics, the physical properties of the n-type GaN layers are of utmost importance. In the MOCVD growth of GaN, the doping process with silicon as dopant is relatively simple and straightforward. 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 silicon as silicon precursor. The influence of the silicon 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 p-side) on the electrical quality of the material is evaluated. The intensity of the photoluminescence (PL) signal and the peak position of the donor-acceptor pair (DAP) transition (towards lower energy position) increases due to conduction band renormalisation. The donor-acceptor level shift towards lower energy position with increasing silicon concentration 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 and transmission electron microscopy (TEM) 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 W5.30

Thin films incorporating 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 a 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: (i) map and depth profile strain in the films, where the strain is due to the lattice mismatch mentioned earlier; (ii) map and depth profile defect distributions; (iii) investigate zinc blende inclusions in thin films of predominantly wurtzite material, and (iv) 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 grown on an epitaxially layered overgrown GaN (ELOG) layer. We have shown that the luminescence efficiency of both the GaN and the MQW is improved for material lying along the straight line from the Sb2O3 peak 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 - MOCV, HVPE, BULK
Chair Hiroshi Amano
Wednesday Morning, December 1, 1999
Room S002 (H)

8:30 AM W6.1
COMPARISON OF InGaN LAYERS GROWN ON BULK GaN AND SAPPHIRE SUBSTRATES. Shiro Sekiguchi, Tokushima University, Dept of Electrical Electronic Engineering, Minami-jojima-ku, 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 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 MOVCVD. Doping of the sapphire substrates with indium had no effect on the 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-micro-rings-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 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 InGaN lattice relaxation 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

Nitrized-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 nitrized-based UV emitters, specifically the control of structural coherence and the enhancement of optical efficiency, are discussed in this work. It is shown that the common configuration of nitrized-based visible-light emitters, based on the growth of ternary (AlGaN and GaN) 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 ternary mismatch to GaN. Two approaches to circumvent this problem will be discussed in this paper: i) the use of a thick AlGaN ternary buffer and ii) the employment of quaternary AlGaN-N as wider bandgap nitrized hetrostructures lattice-matched to GaN. The viability of the employment of binary GaN as 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 Co., for the Department of Energy, under contract DE-AC04-94AL85000.

9:30 AM W6.3
HOMOEPTAXIAL GROWTH ON MISORIENTED GaN SUBSTRATES BY MOCCVD. A.R. Zuerler, 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, National 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 [0001] 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 epitaxially suitable for homoepitaxial growth, this is in contrast with the Ga-side that cannot be mechano-chemically polished. For device application, the formation of hexagons on the 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 homoepitaxial GaN layers grown by low-pressure MOCCVD was studied for different off-angle orientations, 0° and 4°, from the [0001] 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 msV as expected for homoepitaxial growth.

9:45 AM W6.4
CRITICAL LAYER THICKNESS OF GaN/In,Ga1-x,N SYSTEM. C.A. Parker, M.J. Reed, J.C. Roberts, S.X. Liu, N.A. El-Masy, and S.M. Belhar Dept of Electrical and Computer Engineering, NC State Univ, Raleigh, NC; Dept of Materials Science and Engineering, NC State Univ, Raleigh, NC.

Much effort has been directed towards the use of In,Ga1-x,N/GaN heterostructures for device applications where the strained In,Ga1-x,N layers were kept below the so-called critical layer thickness [CLT]. No definite information is available about the value of the critical layer thickness of In,Ga1-x,N heterostructures or double heterostructures (DH) on thick GaN. We present an approach to determine the critical layer thickness of In,Ga1-x,N heterostructures grown by atmospheric MOCCVD. The In,Ga1-x,N films investigated have values of x between 0.0 and 0.20 as determined by x-ray diffraction and thickness of up to 1µm 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 resistance as the In,Ga1-x,N film thickness is increased. As the In,Ga1-x,N 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 resistance, and relocation in free carrier density mark 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,Ga1-x,N/GaN interface, occurs when the film thickness exceeds the CLT. Both approaches give equivalent critical thickness values for the In,Ga1-x,N films and are confirmed by electrical measurements of the samples. The critical layer thickness estimates determined in this fashion are consistent with other x-ray diffraction and SEM observations of surface morphology. It should be noted that our estimates of CLT in the In,Ga1-x,N/GaN system are larger than those previously reported for other semiconductors. We will discuss the nature of the relaxation process in In,Ga1-x,N heterostructures and DHs and report the CLT of the In,Ga1-x,N as part of these structures. Additionally, we will discuss the effect of In,Ga1-x,N thickness on the electrical properties of the In,Ga1-x,N/GaN structure.
10:50 AM W6.5

AI N WAFERS FABRICATED BY HYDRIDE VAPOR PHASE EPITAXY. A. Nikitin, I. Nikitin, A. Zabotin, M. Mykhalev, Ioffe Institute and Crystal Growth Research Center, St. Petersburg, RUSSIA; Yu. Melnik and V. Dmitriev, TDI, Inc., Gaithersburg, MD.

AI 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. In our work we investigate technological difficulties of growing GaN, using the CVD technique, on AlIN substrates (>1µm) that have been reported elsewhere [1]. We demonstrate that using our CVD technique we can grow high quality GaN layers on AlN substrates, which are suitable for high performance device applications. The detailed investigation of structural and optical quality of the grown GaN layers was presented.

11:15 AM W6.6

GROWTH OF CRACK-FREE THICK AlGaN LAYER AND ITS APPLICATION TO GaN BASED LASER DIODES. Tetsuro Komiya, Dept. of Electrical and Electronic Engineering and High-Tech Research Center, Meijo University, Nagoya, JAPAN; Toru Sato, 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, heteroepitaxial growth has been one of the most important key technologies. A thick AlGaN alloy with higher AlIn mole fraction is difficult to grow on sapphire substrate, because the alloy layer is easily cracked. It is thought that the reason 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 AlGaN/GaN n-type layer with the thickness of more than 1µm using underlaying AlGaN/GaN p-type layer. The underlying AlGaN/GaN p-type layer is directly grown on the low temperature-grown buffer layer. Since a lattice mismatch between the underlaying AlGaN/GaN p-type layer and top AlGaN/GaN n-type layer is small, the generation of cracks is thought to be suppressed. This technology is applied to a GaN-based laser diode structure, in which thick AlGaN/GaN clad layer grown on the underlying AlGaN/GaN n-type layer improves optical confinement and single-mode for field pattern in vertical direction. The threshold current is as low as 25mA in a 3µm ridge stripe laser structure, which is comparable to or better than that of conventional GaN-based n-type laser diodes. This result indicates that the quality of epitaxial layers is sufficient for the performance of laser diodes.

11:50 AM W6.9

STRAIN ENGINEERING IN AlGaN/GaN QUANTUM WELLS. Michael E. Aumer, S.F. LeBoeuf, F.G. McIntosh, S.M. Bednar, North Carolina State University, Dept of Electrical and Computer Engineering, Raleigh, NC.

The large lattice mismatch between AI, GaN, and 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 affected 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 quantum-assembly AlInGaN. A test structure was designed to vary the stress experienced by an InGaN/GaN quantum well. The structure is a lattice-matched InGaN/GaN quantum well with a modified barrier permits pseudomorphic quantum wells (QWs) grown on the InGaN/GaN quantum well structure; therefore, if x > 0.1, the well is subjected to tensile stress. InGaN/GaN QWs are created in the well for x < 0.1. Compared to the peak position of the lattice matched AlGaN/InGaN/Si/AlInGaN quantum well, we observed a redshift in the luminescence for the tensely stressed case and a blue-shift in the luminescence for compressive stress. Also, we observed strain-related changes in the current-concentration profile and the two-dimensional electron gas using capacitance-voitage 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.
these conditions can shed light on the surface kinetics relevant to device fabrication. We have conducted a real-time growing 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 1050°C leads to faceting (step branching). 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-DM under contract W-31-109-ENG-38, the NSF under grant DMR-9702401, 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 Dimitrijevic - TDI, Inc.
Paul Chou - Reensak Politechnic Institute
Michael Shur - Reensak Politechnic Institute
John Zwaan - Army Research Office
John Zingle - Office of Naval Research

SESSION W8: GROWTH - MBE, CUBIC GaN, GaAN, 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.U. Wang, Department of Electrical Engineering, Columbia University, New York, N.Y.
High quality AlGaN/GaN has been achieved by molecular beam epitaxy (MBE) using ammonia as the nitrogen source at a growth rate of 1 µm/hr. All samples were grown on c-plane sapphire substrates in a GEN II MBE system equipped with a microwave plasma ion source 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 film. 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 cm²/V·s at 77K. 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]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]N heterostructures at the Paul Drude Institute for Solid State Electronics, Berlin, Germany. The main results are the following:

1. The growth of cubic GaN layers was achieved on both sapphire and [Al,Ga]N buffer layers.
2. The cubic GaN layers exhibit a high degree of orientation and have a hexagonal structure with a growth rate of about 1 µm/hr.
3. The grown layers show a high quality with a threading dislocation density of about 10⁸ cm⁻².
4. The grown layers can be used for the fabrication of optical and electronic devices such as lasers and LEDs.

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

8:30 AM #W9.1 INDIUM AND Sb INDUCED CHANGES IN THE MORPHOLOGY

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°C, resulted in a 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 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 µm) GaN layers. For layers thicker than 1.5 µm, the width of the (0002) AlN 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 µm) GaN layers by hydride vapor phase epitaxy. Structural and optical properties of thick GaN layers will be presented.
OF GaN(0001) GROWTH SURFACES. J.E. Northrup, Xerox Palo Alto Research Center, Palo Alto, CA.

Because of their use as active regions in blue-light emitting diodes and lasers, there is a large interest in InGaN-GaN alloys. A number of interesting phenomena have been observed in the course of epitaxial growth of GaN and InGaN, 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. Results of these calculations are relevant to the formation of the IHP defects that terminate dislocations threading to the surface of the films. These defects are high-angle dislocation pits with sidewall facets consisting of six [101] 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 [101] surface energy. This reduction in energy is traced to the existence of binding sites for the In surface segregation and it is found to be significant. Detailed comparison was made with our experimental data for the diffusive release of H from implantation-formed H bubbles in n-type GaN at 700-800°C. Quantitative agreement was obtained for the magnitude and temperature dependence of the diffusion flux when the energy difference between gaseous H2 and lattice H at increased from a theoretical value of 2.6 eV to 3.8 eV. Our simulations of Mgdoped polycrystals are generally consistent with the 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. Boguslawski, K. K. Bhat, K. H. Bube, and J. Nagel. Department of Physics, NC State University, Raleigh, NC.

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/V 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 wurzite phase, for both the (0001) covalent-polarity and the (0001) nitrogen-polarity surfaces. In agreement with recent experiments we find that mixed AlGaN surfaces prefer Ga termination, and AlN and GaN surfaces prefer In termination. The calculated segregation energies for covalent-rich conditions of growth are unexpectedly large, up to 0.5 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 further reduce 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. Toaska K. Zywietz, Joerg Neugebauer, Matthias Schefler, 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. Analyzing many different In-containing surfaces we find that the monolayer of indium reduces the surface energy of GaN (0001) and (0001) relative to the cleaved equilibrium surfaces. Based on the plane wave calculations the kinetics of Ga and N-atoms 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 phonon coupling and 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 indium. In [1] F. Widmann et al., Appl. Phys. Lett. 73, 2624 (1998).
11:15 AM W9.7
MG SEGREGATION, DIFFICULTIES OF P-DOPING IN GaN
Z. Liikala-Woehr, M. Benhamm, W. Swider, and J. Washburn,
Materials Science Division, Lawrence Berkeley National Laboratory,
Berkeley, CA; I. Gregory and S. Porowski, High Pressure Research
Center, University of Warsaw, Poland, AND
R.D. Dupuis, Microelectronics Research Center, The University of
Texas at 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 doping
through Mg diffusion to the GaN surface layer (9x10^{16} cm^{-2}). Transmission
electron microscopy shows formation of Mg rich defects but their atomic structure
depends on crystal growth polarity. For growth with N polarity spontaneous ordering of Mg rich
plasmic defects is observed. These defects are monolayers of cuboid structure forming a dense network of dislocation loops. 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 heterostructures 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, M.J. Scanlon, Dept.
of Electrical Engineering and Computer Science, State University of
New York at Stony Brook, Stony Brook, NY.

Ion implantation permits the controlled introduction of any desired acceptor doping 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 heterostructural GaN
grown by hydride VPE. Relatively low doses (averaging 1x10^{15}, 1x10^{16},
or 1x10^{17} cm^{-2}) 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-implant annealing in a nitrogen ambient was performed using relatively small (100x10 cm²) 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 294 meV. Blue PL emission is observed at 2-5 K for acceptor-bound exciton, and extremely weak donor-acceptor pair emission, in a stark
contrast to Mg; the acceptor level is, however, somewhat shallower than Mg and its emission is less strongly phonon coupled. The C implant yields no acceptor level. Be and Mg implants produce dose-correlated yellow PL, tentatively
attributed to residual implantation damage. The poor optical activation of Be and Mg may be related to insufficient vacancy
formation by these lighter ions; co-implantation experiments are planned to test this idea.

11:45 AM W9.9
GaN VACANCIES AND NEGATIVE IONS IN Mg DOPED GaN
BULK CRYSTALS. K. Szurmin, J. Nissali, P. Haanjoj, Laboratory of
Physics, Helsinki University of Technology, FINLAND; J. Likonen, Technical Research Centre of Finland, FINLAND; T. Suski, I. Gregory, 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 mostly due to the residual oxygen atoms acting as shallow donors. Previous positron annihilation experiments [1,2] have shown that Ga vacancies are formed during the growth of such GaN bulk crystals and epitaxial layers. When GaN is doped with Mg or Be the electric concentration decreases and for sufficiently high amount of Mg dopants the specimen becomes 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 O or (ii) an electrical compensation of O donors by Mg acceptors. In this work we apply positron annihilation spectroscopy to investigate 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 results are in good agreement with the theoretical calculational ions, which predict a low formation energy for the Ga vacancy and Ga-O, O complex only in n-type material [3,4]. The positron lifetime experiments as a function of temperature indicate that negative ions defects trap positive charges in the addition to 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 Mg2+. The position 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 Mg2+ to Mg and 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 changing them negatively. [1] K. Szurmin et al., Phys. Rev. Lett. 79, 3020 (1997). [2] K. Szurmin et al., Appl. Phys. Lett. 73, 3253 (1998). [3] J. Neugebauer and C.G. Van de Walle, Appl. Phys. Lett. 69, 505 (1996). [4] T. Mattila and R.M. Nieminen, Phys. Rev. B 55, 8571 (1997).

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

1:30 PM W10.1
OHBM CONTACTS TO p-GaN. Szurmin E., Molynex, Joan S., Kwok,
Beecham, John M., Dellacorte, Dept. of Materials Science and
Engineering, Penn State, University Park, PA; Hari S. Venugopalan,
J.C. Raman, Emcor Corporation, Somerset, NJ; Jung Heo, 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 plagued limitations on device performance. In the last year,
however, numerous reports by several independent research groups have described improvements in these contacts, sometimes resulting in ohmic
contacts with specific contact resistances in the 10^{-7} ohm-cm² range
or better. Approaches to achieving reduced contact resistances include
not only the selection of novel metalizations, 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 metalization 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. Lumie, V. Chaturvedi, X. Hu, University of South Carolina, Dept. of ECE, Columbia, SC; M. Shur and R. Gaska, Remsieber Polytechnic Institute, ECSE and CHEM, 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 our development of selective area growth of GaN layers and greatly improved contact metallization schemes with contact resistance as low as 1x10^{-7} Ohm-cm² at room temperature and 1x10^{-6} Ohm-cm² at 250°C. In particularly we demonstrate that using selective growth of top n-type layer in GaN p-n p JFET allows us to avoid the processing degradation of p-type layer. All the GaN layers for this study were grown on sapphire substrates using a standard low pressure MOVCD process. Si and Mg were used as the p-type dopants. For high quality fabrication 0.2 μm thick p-GaN layer (hole concentration of 1x10^{17} cm^{-2}) were grown on a 1 μm thick n-layer. Our p-contact metal scheme consists of Cr-Fe-Au deposited Pt (50 Å)/Au (100 Å) layers. Post deposition, a Sb interdiffusion anneal in a nitrogen ambient was used. TLM (Transmission Line Model) measurements were performed using 2 - 20 μm 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} \text{cm}^{-3}$. GaN n-p-n BJT structures were fabricated, with the top n-layer deposited only in selected areas ranging from 100 to 1500 microns in diameter. Gallium was vapor deposited on top of the n-regrown layer at a temperature of 350°C. The leakage current varied from 15 μA at 25°C to 60 μA at 300°C for 1000 micron diameter. Our results show that bipolar junction transistors fabricated using this metallization scheme and regrown n-layer demonstrate differential gain $g_{m} \approx 10$ at 300°C.

2:15 PM #W10.3

High ohmic contact resistance and low bulk conductivity of p-type nitrides are among the major difficulties encountered in the development of gate-defined linear devices and heterojunction bipolar transistors. In order to overcome these difficulties, methods must be found to increase the ionization efficiency of the Mg acceptor. One such method is to use GaN/AlGaN superlattices. The use of a SL creates a cascade in the valence band-edge that when superimposed in 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 SLs. The hole concentration in the SL increased to 3.5x10^{18} \text{cm}^{-3}. As a result, as-deposited Ti/Pt/Au contacts fabricated on a 2x-period AlGaN/GaN SL showed specific contact resistance under 1x10^{4} \text{Ω} cm², while a 5x-period AlGaN/GaN SL showed specific contact resistances of less than 1x10^{4} \text{Ω} cm². In contrast, the same metallization scheme showed Schottky behavior on p-GaN with nominal doping concentration of 3.5x10^{18} \text{cm}^{-3}.

2:30 PM #W10.4
FORMATION OF QUALITY Pt OHMIC CONTACTS TO N-TYPE GaN USING TWO-STEP SURFACE TREATMENT: Joo-Sook Jang, Han-Kyu Kim, Kyung-Mo Yoo, Seok-Young, Department of Materials Science and Engineering, Kwangju Institute of Science and Technology (KJIST), Kwangju, KOREA.

GaN and III-Nitride layers have been extensively investigated, especially the realization 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 steps are performed after the metal etching process using buffered oxide etch (BOE) and ammonium sulfamate etch. This is followed by the second step using BOE. The contact property is found to significantly depend on the surface-treatment conditions. The Pt contact that was simply BOE-treated yields a specific contact resistance of 2x10^{-1} \text{Ω} cm². However, the contact was sequentially etched by BOE (10 min) and NH₄OH (10 min) 2x10^{-1} \text{Ω} cm². 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 different surface-treatment conditions 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 treatments also show that it is possible to investigate the electrical and thermal stability of the contact 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. Lock, Wright State University, Semiconductor Research Center, Dayton, OH.

Defects, point defects and line defects (dislocations), can act as acceptors, donors, or 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, it is understood that line 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 MOVCD 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-resolution electron-irradiation experiments, and, so far, electrical and/or optical “fingerprint” 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 its infancy, with the first papers appearing only two years ago. In high-doped p-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 is shown that the dominant donor in the “best” (μm) n-GaAs and in the “best” (μm) n-GaAs is probably $O_N$ or $S_G$. 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 n-GaAs, 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.
Recent interest in GaN-based devices has stimulated studies on p-type doping issues as well as the search for novel ohmic contacts. The role of hydrogen in the passivation and activation of dopants in MOCVD grown material is recognized, nevertheless its behavior is not fully understood. This study addresses the problem of the possibility of removing hydrogen from the near-surface region in p-type GaN. The accumulation of hydrogen in areas of high defect density has been recently evidenced. It is therefore very likely that hydrogen could be accumulated at the surface of p-GaN. As a consequence, the substrate volume may contain a lower free carrier concentration than the bulk. We have studied this problem using p-GaN/Mg grown on SiC. To facilitate the evolution of hydrogen from the surface of p-GaN, the release of hydrogen from p-GaN via Zn- or Zr-based cap films is recommended. Zirconium is one of the highest absorptive capabilities for hydrogen of metal hydride systems, while Zn and Zr are distinguished for their exceptional low resistivities and high melting points. Hydrogen depth profiling was performed using a Cameca SMX. The thermal stability of Zn-based caps on GaN has been investigated using TEM. The electrical characterization of metal/p-GaN systems involved measurements of L/V characteristics and resistivity of ohmic contacts. Our results prove a significant accumulation of hydrogen in the substrate region and its measurable level in the bulk of p-type GaN. After thermal processing at temperatures above 700°C, the release of hydrogen from p-GaN via Zn-based cap is observed. The system remains stable even after processing at 1150°C. No hydrogen was detected in caps annealed. Removal of hydrogen was found to promote the formation of ohmic contacts. C.C. Van de Walle, N.J. Johnson, Semiconductors and Semimetals, 57, 157 (1999) M. Murakami, Y. Koid, Critical Rev. Sci. Tech. Mater., 23, 1 (1998) T.J. Pearton et al., J. Vac. Sci. Technol. A, 14, 831 (1996).

SESSION W11: POSTER SESSION

W11.1
Type of Paper: Technical

W11.2
Type of Paper: Technical

W11.3
Type of Paper: Technical
Microstructure Nanjing University, Nanjing, CHINA; Z.C. Huang Raytheon ITSSS, Baltimore, MD.

GaN-based metal-ferroelectric-semiconductor (MFS) structure has been fabricated by using ferroelectric PbZr0.53Ti0.47O3 (PZT) instead of conventional oxides as insulator gate. The Electric properties of GaN MFS structure are characterized by high-frequency C-V method and radiante Technologies Pulsed Testing System (RT6000HV8). The current leakage of PZT deposited on GaN is as low as 10⁻¹¹ A. The polarization of PZT under 5V bias is about 4.7±0.6 C/m². 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 structures are markedly improved compared to that of otherwise previously studied GaN MIS structures. The GaN surface layer in MFS structures can reach inversion just under the bias of smaller than 5 V, which is generally applied voltage used in semiconductor-based integrated circuits. The dielectric constant of the 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.


We report the growth and characterization of high-quality AlGaN/GaN epilayers grown by low-pressure chemical vapor deposition (MOCVD) in hydrogen with trimethylgallium (TMGa), trimethylaluminum (TMAI), silane (SiH4), and ammonia (NH3) precursors. We have varied the growth conditions e.g., growth temperature, V/Ar 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 gases (2DEGs). 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 Hall measurements of the 2DEG films show no strong correlation between symmetric (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 0.5° mm area show RMS roughness values between 0.5 and 1.0 nm independent of the measured mobility. Samples with 2DEG mobility in the 2DEG 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 2DEG, consistent with the electrical data.


There have been numerous reports on high quality AlGaN/GaN heterostructures grown by MOCVD with electron mobilities as high as 2050 cm²/Vs and 9000 cm²/Vs (carrier density 1x10¹² cm⁻²) at 300K and 77K, respectively (Gaska et. al, APL, 1999). Two-dimensional electron gases (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 heterostructures were used for the AlGaN/GaN growth. Unintentionally doped MBE GaN was grown at 750°C 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 cm²/Vs, 72% of the bulk value of 1.5000 cm²/Vs increasing to 20,000 cm²/Vs at 4.2K. The sheet carrier concentration varied from 1.4x10¹² cm⁻² at room temperature to 4.8x10¹¹ cm⁻² at 1 K. Because the sample was grown on n-type MOCVD GaN a parallel conduction path of low mobility carriers exists and significantly affects the room temperature measurements. The magnetic field dependence of the longitudinal resistance of the AlGaN/GaN heterostructure at 4.2K showed Shubnikov-de Hass oscillations starting at about 2.5 T that confirm the existence of a 2DEG at the AlGaN/GaN heterostructure interface. By optimizing the heterostructure a 12K mobility of 50,000 cm²/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 HETERO-STRUCTURES. A. Michel, Dept. of Chemical Engineering, D. Haner, R.F. Davis, Dept. Materials Science and Engineering, North Carolina State University, Raleigh, NC; D. Qin, S.S. Lau, L.S. Yu, W. Sun, P. Asheek, Electrical and Computer Engineering Department, University of California San Diego, LaJolla, CA.

Gallium nitride-based high-mobility bipolar transistors (HTB) are promising power devices for compact, efficient power supplies. A key issue in the development of nitride-based HTB is a more conductive buffer layer. Conventional p-type Si substrate is 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 grown by MOVPE on Si substrates at 450°C and 1000°C. Graded AlGaN and GaN epilayers were doped with Mg from a metalorganic magnesium source, and the films were subsequently annealed at 800°C in nitrogen. It has been demonstrated that piezoelectric effects from AlGaN/GaN heterostructures significantly contribute to conductivity in the base material relative to conventional Mg doping. Hall measurements were performed on the heterostructures to determine the effect of piezoelectric doping on mobility and conductivity. At room temperature, the sheet conductance of the film that incorporates piezoelectric effects along with Mg doping exhibited a sheet conductance of 2x10⁴ cm²/Vs compared to Mg-doped GaN that exhibited a conductance of 7x10² cm²/Vs. 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 HETERO-STRUCTURES ON SiC AND SAPPHIRE SUBSTRATES. P. Pala, G. R. Gaska, M. Sharif, J.W. Yang, and M.A. Khan, 2nd Department of Physics, Rensselaer Polytechnic Institute, Troy, NY, Department of ECE, University of California, Columbia, SC.

We report a comparative study of the low-frequency noise in AlGaN/GaN heterostructures grown on SiC and sapphire substrates 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 9x10²⁵ cm⁻² and 1000 cm²/Vs, respectively. The noise showed that the noise in the AlGaN-GaN heterostructures and the SiC substrates is dominated by the Noise Spectral Density (NSD) zero gate bias was nearly the same and decreased with increasing the spacing between the TLM contacts. We link this decrease in NSD in SiC with the increase in a total number of carriers in the 2D channel. The NSD exhibited strong dependence on applied gate bias, Vgs. The noise in the samples with 100 mm thick SiO₂ layer between AlGaN barrier and the gate electrode decreased monotonously with increase in Vgs from -18 V up to -2 V. We attribute this increase in the sheet density in the channel, which is in good agreement with the noise theory. In contrast, NSD in heterostructures without the isolating SiO₂ layer sharply increased for both positive and negative gate bias beyond the range of the gate voltage. The dependence on gate density in the heterostructures grown on 6H-SiC using the conducting substrate as a backgate. This allowed us to modulate the electron density in 2DEG at AlGaN/GaN heterostructure. 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 CHARACTERIZATION OF AN AlGaN/GaN TWO-DIMENSIONAL ELECTRON GAS HETERO-STRUCTURE. A. Sager, D. Deluca, R. Perrin, S. Elhmami and W.C. Mitchel, Air Force Research Laboratory,Materials
An Al,Ga1-xN/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 0.21±0.02 based on the temperature dependence of the Hall mobility of the Shubnikov-de Haas oscillations. The quantum lifetime was substantially lower than the transport lifetime of 2.3x10^-15 s which is based on a mobility of 1.9 x 10^5 cm^2/Vs measured by the Hall effect. The sheet carrier concentrations determined by Hall and Shubnikov-de Haas were in good agreement at 5x10^12 cm^-2 indicating absence of parallel conduction. Magnetic field dependent Hall effect analysis also showed negligible parallel conduction at low temperatures. X-ray diffraction measurements were consistent with that of 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 HETEROSTRUCTURES. Michael J. Manfra, Loren N. Pfeiffer, Denis Buchmann, 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 change the charge distribution at AlGaN/GaN interfaces. Hexagonal, or wurtzite, GaN lacks inversion symmetry along the c axis. It gives rise to 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 Sion 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 zincblende 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 heterostructures grown by plasma nitride molecular beam epitaxy. Cubic structures were grown using the [100] face of GaN as an epitaxial template. The structure consists of 500nm of GaN capped with 40nm of AlxGa1-xN. 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 GaN crystal growth. 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 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 HETEROSTRUCTURE 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 AlxGa1-xN/GaN heterojunction field effect transistor (HFET) structures grown on sapphire substrates with high sheet carrier density and mobility products (n~μ~1.4 x 10^16 cm^-2 V^-1 s^-1 as 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 Sidoped AlGaN layer thicknesses and the Sidoping concentration. In these structures, the persistent photocurrent (PPC) effect associated with the two-dimensional electron gas (2DEG) spatially separated from the n-type channel, is a characteristic parameters of the 2DEG were sensitive to light and the sensitivity was associated with permanent photodiffracted increases in the 2DEG carrier mobility and sheet carrier density. However, we observed that the magnitudes of the PPC and hence the photodiffracted instability associated with these heterostructures were a strong function of only one parameter, the product of n ~ μ, which is the most important parameter for HFET device applications. For a fixed excitation photon dose (excitation intensity × excitation time), the ratio of the low temperature PPC to the dark conductivity level was observed to decrease from 200% to 3% as the n ~ μ 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 ZINCBLLENDE PHASE GaN MESFETS. Muzaffar Fahamuddin 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 selfconsistent, 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 cut-off frequency than the wurtzite phase. 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 μm 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 138 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, Tokei Somym, Masuo Nishikita, Yosuke 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 experimental result and the theoretical calculation. Since the relaxation of an AlGaN layer on GaN is determined by the thickness of the AlGaN layer, the influence of the thickness of Sidoped 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 mole 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 as the AlGaN barrier is relaxed. The critical thickness of the AlGaN layer on GaN is determined by 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 the AlGaN/GaN interface. The feasibility Al0.4Ga0.6N/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. Abrecht, P. Ruten, University of Minnesota, Department of Electrical and Computer Engineering, Minneapolis, MN; S.C. Basu, K. Ikossi-Annast, M.G. Arcoa, Naval Research Laboratory, Electronics Science and Technology Division, Washington, DC.

A new, self-consistent model for the output characteristics of AlGaN/GaN field-effect transistors is presented. The model is based on Monte Carlo simulations of the relevant electron transport characteristics and their temperature dependence. Temperature effects due to incomplete thermalization in the devices are incorporated selfconsistently. Furthermore, the model fully takes into account the unguided access channels between source and gate and between gate and drain. These access channels, which in conventional models are represented as linear parameters, do 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 characteristics are found to be in agreement with reported data for AIGaN/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 in the ultimate origin of current saturation in these devices. The relative importance of the individual saturation effects is controlled 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. Weslaski, US Army Research Laboratory, Sensors and Electronic Devices Directorate, MD; S. Jiang, 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 photogain. However, ZnO photodetectors usually exhibit either a large photoreponse with a slow speed or a high speed with a small photoreponse. In this paper we report ZnO MSM detectors grown on R-plane sapphire, which exhibit both high photoreponse 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 photodetectors were fabricated on the epitaxial ZnO films. Al was used as the contact metal because of its low electron-affinity. The photoreponse of the detector was measured with a lump and monochromator combination. A sharp photoreponse with a cutoff wavelength (20 dB above 15 nm) at 375 nm was observed. The photoreponses of this device exhibits a linear dependence upon bias voltage up to 10 V with a photoreponse of 400 A/W at 5 V. The speed of the device is measured with a 100 fs, 300-500nm 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 photoreponse of ZnO consists of two parts: a rapid solid-state process (as usually with NH3 doping) and an O2 adsorption (with a large response). This slow photoreponse 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 processes is enhanced in our sample by the improvement of crystalline-quality that reduces the defect-induced recombination. Simultaneously, the O2 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 AIGaN/GaN DISTRIBUTED BRAGG REFLECTOR ON SAPPHIRE GROWN BY MOCVD. Takashi Egawa, Naoyuki Nakata*, Hiroyasu Ishikawa, Takashi Jimbo and Masayoshi Umemo, Research Center for Micro-Structure Devices, Nagoya Institute of Technology, Gokiso-Cho, Showa-Ku, Nagoya 466, 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) has been the key technology for the successful VCSELs. In this study, we report A0.75Ga0.25N/GaN DBR on a sapphire substrate with (001) orientation (c face) grown by MOCVD. The structure consisted a 30-mon thick GaN buffer layer at 1000°C, 1.5 µm thick GaN layer at 1000°C, 180 periods of A0.75Ga0.25N/GaN strained laser cavities (SLs) and 30 pairs of quarter wavelength A0.75Ga0.25N/GaN DBR. For comparison, the DBR structure without SLs has also been grown on sapphire. The DBR without SLs showed the cracks, the rough surface morphology and the reflectivity of 99%. On the other hand, the DBR with SLs exhibited the peak reflectivity as high as 99% 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 A0.75Ga0.25N layers in the DBR with the SLs was confirmed by the Auger electron spectroscopy measurement. The reflectivity as high as 99% has been achieved for the A0.75Ga0.25N/GaN DBR by use of A0.75Ga0.25N/GaN SLs, which is promising for the GaN-based VCSELs on sapphire.

W11.18 THERMAL DISTRIBUTION MEASUREMENT IN InGaN-MQW LEDS UNDER OPERATION. Veit Schweger, Christoph Kirchner, Maxime Seybold, Markus Kump, University of Ulm, Dept. of Optoelectronics, GERMANY; Wolfgang Limmer, Ulrich Sempf, 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 metal) as well as migration of dopants. 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 E3-LO phonon scattering (Ramans), finite element simulations, and spatially resolved electroluminescence (EL). The region of increasing 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 W/cm²) temperatures as high as 140°C are determined in LEDs. These 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.


Photopumped surface-mode lasing at 400-415 nm is achieved in InGaN/GaN/InGaN heterostructures grown on sapphire substrate using metal-organic vapor phase epitaxy. Structures were grown at ambient pressures in the range of 15-250 mtorr 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 rotating substrate temperature-cycling technique either on top of a GaN buffer layer [2] or on top of a strain-compensated AIGaN/GaN Bragg mirror [3]. For the structures, where Facory-Perot cavity was formed just by the GaN/sapphire and the GaN/sapphire interfaces the threshold excitation density (~220 kW/cm²) is weakly affected by the temperature of observation up to 110K while it increases at 300K to 1 MW/cm². 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/cm². The best condition is the 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 lowest-wavelength side of the PL spectrum. Thus, the lasing clearly occurs via the localized states caused by In-rich nanodomains manifested in TEM and in optical studies. As opposite, the structures grown without bottom DBRs show lasing on the high-energy side of the PL emission spectrum. [1] I.I. Krestnikov et al, Phys. Rev. B, 50, July 1999. [2] A.V. Sukhorukov et al, Appl. Phys. Lett., 74, 28 June 1999. [3] I.I. Krestnikov et al, Appl. Phys. Lett., in print.


In GaN/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 performance. 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 not a detailed experimental results on the impact of Si doping on the performance of the 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/cm²) photoluminescence properties were affected by piezoelectric effects, and the peak
energy position and the peak intensity increases with Si doping level. Next, we grow vertical 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/AlₓGaₙN BRAGG REFLECTORS. Fritz Fedler, H. Wurzeni, J. Aderhold, D. Mietze, J. Steen, O. Sentrichov, J. Graul, Laboratory for Information Technology, Univ. of Hanover, Hannover, GERMANY; J. DinhViet, S. Prasser, 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. Screening E-Beam pumping experiments were performed at 40 kV excitation electron energy and 80 K to characterize the influence of GaN/AlₓGaₙN distributed Bragg reflectors (DBR) on the responsivity properties by observing the surface emission spectra of the vertical cavity structures. The sample structures were grown by plasma-assisted molecular beam epitaxy (PA-MBE) using a CAR925 from Oxford Applied Research. The active region of the two samples consisted of a 1.2 µm thick Si doped GaN layer and accordingly of a 1.2 µm thick 8.5-period multilayer (MH) structure based on GaN/AlₓGaₙN, which was grown on a vertical cavity formed by 15 periods GaN/AlₓGaₙN distributed 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 ɑ-beam currents and showed that luminescence emission maximum was located around 3.45 eV or 88 K for the sample with the MH structure as active region. Above an excitation power density of 0.85 MW/cm² 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 position of the primary beam electrons on the surface layer and on the optical parameters of the nitride vertical cavity will be discussed and a search for other studies on ɑ-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. Sung, 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 laser threshold was measured to be 0.47 W/cm² and 100 kW/cm² at room temperature. Strongly polarized (TE:TM > 99.99) 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 GaN and GaN layers. The mode tuning 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 laser threshold, reveals that excitons are strongly affected by piezoelectric effects. The threshold is found to be 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 diode with a GaN active medium.

W11.23
WAVELENGTH EMISSION FROM GaN/AlN QUANTUM DOT DOTS GROWN ON SILICON (111) SUBSTRATE. Benjamin Donnell, Nicolas Grandjean, Fabrice Semond, Jean Massies, Mathieu Leroux, Centre National de la Recherche Scientifique, CRHEA, Rue B. Grégoire, Sophie Anippli, Valbonne, FRANCE.

GaN quantum dots (QDs) in AlN matrix were grown on Si (111) by molecular beam epitaxy using amonia as nitrogen precursor. The growth mode and relaxation process of GaN deposited at 800°C on an AlN 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 partial relaxation which occurs at 12 monolayers [ML, 1 ML = 5.5Å]. On the other hand, growth recovery 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 large polarization field which takes place in QD-based heterostructures.

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

An InGaN/GaN multiquantum well (MQW)/LED, which consists of 30 periods of InGaN/GaN MQW, were grown by metalorganic vapor phase epitaxy (MOVPE). The undoped MQW structure consists of 30A InGaN/GaN well layers and 70A GaN barrier layer. The p-type contact is Ni/Au (3/2µm/6µm) ultrathin transparent layers. The output power of a 350°-355 nm size chip was around 1.5mW at 20 mA injection current, and forward voltage of 3.8 V. 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 28mA. If there was strain free in the MQW, one may expect that a high band edge energy gap is obtained inside 480nm. 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 in the injection current range from 60mA to 300mA. The blue-shift and red-shift of electroluminescence could be understood as a result of competition between a spectrum red-shifting mechanism of piezoelectricity-induced quantum-confined Stark effect and a blue-shifting mechanism of band-filling and charge screening effects.

W11.25
DEPENDENCE OF AGING ON THE INBOLOGENIETIES IN InGaN/GaN/AlGaN/TaN LIGHT EMITTING DIODES. V. E. Kryukov, S. M. Iskandar, A. A. Yudovich, A. N. Turkin, A. E. Yudovich, M. V. Lomonosov Moscow State University, Department of Physics; A. N. Kovalyov, F. I. Manyakin, Moscow Institute of Steel and Alloys.

In a recent paper we have shown that mircro defects in quantum efficiency (of 10% at working currents) of green LEDs based on InGaN-GaN-AlGaN/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 devices and the nonuniformities in the heterostructures due to 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 devices and the nonuniformities in the heterostructures due to different distribution of effective charges in the space charge regions and role of tunnel component of currents.

W11.26
OPTICAL SPECTROSCOPY AND COMPOSITION OF InGaN QD. K.P. O'Donnell, R.W. Martin, M. E. White, Department of Physics and Applied Physics, University of Strathclyde, Glasgow, SCOTLAND; Korn Jacobs, W. Van der Stricht, P. Demeester, Department of Information Technology, University of Gent, BELGIUM; A. Vastame, M. P. Wei, KULeuven, Leuven, BELGIUM; J. F. M. Huybers, Unile, Durham, ENGLAND.

The extension of nitride technology to the full visible spectrum is a technical challenge that depends on 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 epitaxial layers 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, 283 (1999)] we predict a limiting value for InGaN intrinsic emission, of 980 nm peak. Although this predicted value is 0.6 eV lower 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 inductance content of a wide range of light-emitting InGaN layers. Different measurement techniques, e.g., 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 inductance content of only 50%. This result is consistent with these results on future technological innovations and current theoretical models of InGaN will be discussed.

W11.27

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/InGaN MQW structures grown by MOVCD on (0001)-oriented sapphire substrates were studied. Theoretically, we calculated the built-in fields (in-and well) in these p-i-nMQW strained structures including the piezoelectric field. Moreover, we performed calculations of the electron and hole wave-function within the quantum well 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-nMQW structures with 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. 2. The magnitude of the yellow emission in the time-integrated spectrum served as an indicator of the magnitude of the built-in p-in electric field and elongation of carrier recombination lifetimes. Furthermore, the time resolved photoluminescence measurement results of InGaN MQW layers showed a 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 A ASYMMETRIC GaN(N)/AlGaN(M) HETEROSTRUCTURES AND SINGLE AND MULTIPLE QUANTUM WELLS ON SAPPHIRE AND SiC. J. Lin, UK, Institute for Superhard Materials, Harbin Institute of Technology, Harbin, P.R. China, Germany.

The piezoelectric field effect in GaN/InGaN quantum wells, which has been recently lively discussed, provides in-depth explanation of their optical properties and gives a new eye to their electrical characterization. In this work, we designed GaN/AlGaN asymmetric double quantum well (ADQW) structure, which consists of 2.5 nm and 4 nm GaN quantum well separated by a 2.5 nm AlGaN barrier. In the presence of the piezoelectric field, we expect different behavior if the position of the two QWs 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 in situ the two inter-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 these ADQWs is compared to the asymmetry in symmetric barrier structures, i.e., a GaN quantum well sandwiched by a 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, we find that the growth direction and SiC substrate of this sample effect the sign of the field. 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/InN QUANTUM WELLS AND THEIR 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/InN MQW (Ix = 0.125, Lz = 4.0 nm, Lx = 7.7 nm) MOVCD grown on GaN/InGaN substrate is investigated applying spatially and time resolved cathodoluminescence (CL), photoluminescence (PL) as well as gain spectroscopy. The excitation density is varied from 1.3 μW/cm² up to 60 kW/cm². The InGaN MQW exhibits a very intense blue emission centered around 2.8 eV (~0.55 eV) containing a 2.0 eV (~1.05 eV) shifting with increasing cw CL excitation power according to E = Eo + 25eVln(x/Po) which is consistent with filling of localized states within the statistical [CL]–distribution. From CL wavelength-images mapping the local emission energy we find an almost Gaussian distribution yielding Eo = 2.841 eV and a standard deviation of σ = 0.7 meV (σx = 0.005). Time resolved CL measurements yield a spectrally dependent carrier lifetime increasing from 88 ns up to 120 ns (with decreasing photon excitation density) and a monotonic redshift of ΔE = 60 meV during 4.5 μs decay (E = Eo+25eVln(x/Po)) directly visualizing the carrier thermalization into In-rich low-energy states. While the GaN luminescence follows Varshni's temperature dependence a strong Sahpepe behavior is observed for the InGaN related emission. Starting at 4.5 K for a PL excitation density of 0.13 W/cm² 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 k W/cm². From an Arrhenius plot of the PL intensity we can determine recombination energies of 22 meV and 8 meV for thermionic emission of the freeze 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
DEFFECTS, PHASE SEPARATION AND COMPOSITION FLUCTUATION IN InGaN LAYERS GROWN BY MOVCD. Pierre Ruterana, Laboratoire d’Etudes et de Recherches sur les Matériaux, UPRERA CNRS 6004, IMSRA, Cen, FRANCE. Marie-Antoinette Poulain, Thomson-CSF, Laboratoire Central de Recherches, Domaine de Coussery, 91401 ORMEUX, FRANCE, Pierre-Oliviers and David Schenk, 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 focused on InGaN layers whose indium composition 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 was closed to 19%. Close examination of the layer surface shows that when threading dislocations emerge, a nanometric precipitate form has formed. EDS analysis shows that these precipitate correspond to InN. In the second series of samples, we found in CL observation a thickening on average above 10% V shape defects forming cross the whole ternary layer. These defects are clearly connected to each others threading dislocations. In many cases more then 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
STABILITY OF PHASE SEPARATED THIN LAYERS OF InGaN GROWN BY METAL-ORGANIC VAPOR-PHASE EPITAXY. P.L. S.J. Chu, Center for Opto-electronics, Dept. of Electrical Engineering, National University of Singapore, SINGAPORE; W. Wu, H.M. Hua, Institute of Material Research and Engineering, SINGAPORE; T. Sugahara, S. Sasaki, Satellite Venture Business Laboratory, Department of Electrical Engineering, University of Tokushima, Minami-Iozenji, Tokushima, JAPAN.

Four phase separated InGaN thin films were grown by low-pressure metal-organic vapor-phase epitaxy (MOVPE) on sapphire substrates and characterized by photoluminescence (PL) with variable excitation intensity and temperature. The temporal and spatial thermalization and carrier freeze out in local potential fluctuations. The effects of dislocations on the growth and emission process was investigated by Atomic Force Microscopy (AFM) and Cathodoluminescence (CL) mapping. All the four samples show distinct peaks at around 3.3 and 2.9 eV at 2.8°C. One sample with a 19.5% In-content determined by HRXRD, has the strongest peak at 2.8 eV 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 8K to 300K. The high energy peak exhibits a red-shift as the temperature is increased from 4K and reaches a peak at about 150K. The low energy peak dominates at 300K. The results of the excitation power-dependent PL and the TRPL technique showed the possibility that the low energy peak comes from DAP. We conclude that the low energy peak is due to the localized non-band emission transition from the phase-separated InGaN nanowires structure with high In-content. The strong luminescence of the low energy peak may be attributed to the formation of nanowires 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 are embedded 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 large (diameter 700nm) and small (diameter 100nm) nanowires which are inverted hexagonal pyramids which are formed at the ends of DPs. The sides of the ‘pits’ surface. Thus, the strong preference for In surface segregation and occupation of {111} surface which was first put forward by Nordrup using the first-principle calculation was demonstrated. CL mapping is being done in Prof. S. Sakai’s group in the University of Tokyo. 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-WELL DUE TO SCREENING OF PIEZOELECTRIC FIELD. A. Knuchel1,2, H. Hirayama2, H. Kojima2, H. Miyasaka2, A. Hojo2, Y. Inoue1, T. Kawai1, H. Ishida1, H. Noda1, Y. Nakayama1. 1Institute of Physics and Chemical Research (RIKEN), Saitama, JAPAN, 2Dept of Chemical Engineering, Waseda Univ., Tokyo, JAPAN.

The screening of piezoelectric field in the QW plays a significant role for increase of emission probability. In this report, the effect of Si-doping on optical properties was systematically studied in GaN/AlGaN single quantum well (SQW) structures. We have grown GaN/AlGaN SQWs by metalorganic vapor phase epitaxy (MOVPE). Structures consist of Si-doped or undoped GaN SQW with 5000nm-thick Al0.1Ga0.9N buffer and 250nm-thick Al0.1Ga0.9N capping layer. Si-doping concentration in the well was varied from 2x 1018 to 7x 1018 cm-2 and their thickness was varied from 2nm to 5nm. Information on the optical properties as well as thickness and/or Si-doping concentration were extracted from 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 shown an increase with increasing Si-doping concentration. The magnitude of these intensity enhancement and blue shift was found to dramatically 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 7x 1018 cm-2. In addition, PL peak energy as a function of well thickness was measured for undoped and highly Si-doped SQW under high excitation 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 indicate that the optical properties of GaN/AlGaN single quantum well was drastically improved due to the screening of piezoelectric field.


InGaN/GaN heterostructures grown in AIXTRON single and multiwavelength production reactors were studied by conventional transmission electron microscopy to assess the morphology of the epilayer 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 on Al2O3 (0001) substrates. A two series of samples were investigated, where only one parameter was varied. In the first series, the InGaN growth temperature was changed during the run on the InGaN growth temperature was varied in the second series. An image evaluation procedure based on high-resolution inverse fringes image was applied to investigation of the InGaN layer. 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-concentration of more than 5% show composition fluctuations on a scale of a few nanometers. The local indium composition increases up to a factor 3 with In-content. The average In-concentration can be strongly influenced by the growth temperature. Higher In-contents are incorporated by lowering the growth temperature from 860°C to 810°C which also induces a red-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 temperature indicate that the average In-contents differ. For a growth duration of 1 min the average In-concentration amounts to 6%, 15% 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 wavelength uniformities of less than 1 nm across a full two inch wafer measured routinely.


Heterostructures of compound group-III nitride-semiconductors are of great importance for the rapid development of a new generation of light sources and detectors. The optical properties of InGaN/GaN heterostructures with various compositions of 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 multiplex 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-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 Hirayama1, Yasushi Enomoto1, Atsushi Kinoshita1,2, Akira Herrs1, H. (RIKEN(The Institute of Physical and Chemical Research), 2Waseda Univ.

AlGaN alloy is very attractive material for the application to ultraviolet (UV) laser diodes (LDs), light emitting diodes (LEDs) or photo-detectors, because of the strong quantum emission range between 3.4 eV (GaN) and 6.3 eV (AlN). In this work, as a trial for the strong UV light-emitting material, we fabricated AlxGa1-xN /AlxGa1-xN MQW structures using metalorganic chemical vapor deposition (MOCVD), and demonstrate intense UV photoluminescence (PL) emission of 260 nm band from the MQW. We fabricated structures of 4.5 μm-thick Al0.1Ga0.9N /Al0.1Ga0.9N MQW with 5-layer thick AlxGa1-xN quantum well and 650 nm-thick AlxGa1-xN barrier grown on 6H-SiC(0001) substrate. We obtained single peak PL emission of 262nm from Al0.1Ga0.9N /Al0.1Ga0.9N MQW with 5nm thick quantum well at 7K. The intensity of the AlGaN MQW at 7K was as strong as that of the InxGa1-xN /Al0.1Ga0.9N single-QW. We systematically studied on optical properties of AlGaN MQWs in terms of quantum well thickness and Al content of the barrier layer. By changing the Al content of barrier layer from 0 to 0.7, we obtained the UV PL peak of MQWs ranging from 333 nm to 260 nm. Also we found that the optimized well thickness for the intense PL emission was around 5nm for various Al content of AlGaN barrier layer. In the conference, we will further discuss the dependence of PL and photoluminescence excitation spectra (PLE) of the AlGaN MQWs.
Associate Radiation Source at 800 C for 10 minutes. After the clearing 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. HIEED was employed to monitor the crystal growth. The growth of GaN buffer layer required particular attention. For low temperatures (700 C), face-like HIEED patterns were often observed. HIEED patterns for the layers grown above 700 C remained strongly 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 result was an InGaN layer formed pure GaN. Photoluminescence of the InGaN quantum wells showed band-edge emissions at 460 nm at low temperatures (10K). TEM studies indicated very good crystalline quality. We deduce that the commonly observed decrease in the photoluminescence intensity with increased distance away from GaN/InGaN interface. The InGaN layers are single crystalline and epitaxial, and revealing clean and uniformly strained interfaces with GaN, and layers of the threading dislocations introduced from the GaN/InGaN interface do not propagate through the InGaN layers. Detailed results will be reported.

W11.40 OPTICAL MEMORY USING BIPHOTONIC UPCONVERSION IN Er FIB IMPLANTED GALLIUM NITRIDE. R.C. Chau, B.K. Lee, L.C. Chao, J. Cheng, I. Chyn and A.J. Steckl, Nano Electronics 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 pump beams at different frequencies 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 two-photon absorption. Experimental results are shown. Further work is planned on this subject.
**W11.14**

**OPTICAL SPECTROSCOPY OF InGaN Epilayers in the Low In Compositional regime.** M. H. Crawford, J. Han, M.A. Baus, G.A. Petersen, S.M. Myers and J.F. Figiel, Sandia National Laboratories, Albuquerque, 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 the localization of excitons in 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 optical properties of the alloy, and little or nothing 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 optical properties vary. 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 intensity is reduced with increased In composition, and varied from a factor of 10 to a factor of 50 for the samples studied. To resolve PL studies have been performed to study the recombination dynamics as a function of In composition and will be reported [1]. L. Parr, et al, J. C. Zolai, Growth 189/190 728 (1998), Sandia's materials program laboratory operated by Sandia Corporation, a Lockheed Martin Company for the U.S. Dept. of Energy under contract DE-AC04-94AL85000.

**W11.14.2**

**ELECTRON RAMAN SCATTERING FROM Mg-DOPED WURTZITE GaN.** H. Jin, K. T. Tsui, C. Koch, Y. Chen, Department of Physics and Astronomy, Arizona State Univ, Tempe, AZ; H. Moroke, Department of Electrical Engineering, Virginia Commonwealth Univ, Richmond, VA; H. Jiang, Department of Physics, Kansas State Univ, Manhattan, KS.

Electronic Raman scattering from heavily Mg-doped wurtzite GaN has been observed using Raman spectroscopy at T = 300 K. Both MgRb-grown and MgCdV-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.

**W11.14.3**

**PROPERTIES OF A BLUE EMISSION BAND OF BULK INGAN.** Hisashi Konie, Takahiro Kaminou, Science University, Dept. of Applied Electronics, Chiba, JAPAN.

Recent advance in growth technique allows InGaN based violet laser diodes to have a lifetime longer than 10,000 hr. The emission mechanism of the laser 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 minute of growth induced stresses. The grown InGaN crystals have a diameter of several mm, a hexagonal structure and showed a broad cathodoluminescence (CL) band with a peak in a range from 2.85 to 2.86 eV at 10K and 0.5 mA. The new peaks emerged with an increase in an acceleration voltage. At 15 K 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 K. We think that the peak shift is attributed to the depth profile of In in the crystal, and the spectrum shown in Fig. 1a demonstrated that the excitation wavelength of light at 2.5 eV 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 at 3.17 eV, which is located in those from 3.26 to 2.4 eV at 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 3.25-nm line. Because the excitation at 2.85 eV, the PL band shape resembled the 2.85 eV one excited by a He-Cd laser. Like the CL bands, the 2.85 eV PL band consists of two bands: an emission band at around 3.4 to 3.5 eV which has a fundamental absorption as an excited state and the one at 2.5 eV which is a fundamental absorption band with the peak at 2.15 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.

**W11.14.4**

**PHOTOLUMINESCENCE CHARACTERIZATION OF Mg-DOPED GaN.** C. Ramon, H. Hoffkess, H. Physicalisches Institut, Universitat Goettingen, A. Stoeter, M. Deicher, Fachbereich Physik, Universitat Konstanz, Konstanz; E.P. Crichton, J.P. Hurlebi, R.F. Davis, Department of Materials Science and Engineering, North Carolina State University, Raleigh, NC.

Single crystalline (0001) g-alumina nitride layers, capped with a thin epitaxial aluminum nitride layer, were implanted with magnesium and subsequently annealed within the range of 1000-1300 °C for 15-60 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 Mg concentration 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 before removing the AlN-cap and the deposition of Pt/Au contacts. These results will also be presented.

**W11.15**

**INVESTIGATION OF LONG AND SHORT TIME-CONSTANT PERSISTENT PHOTOCONDUCTIVITY IN UNDOPED GaN GROWN BY RF-PLASMA ASSISTED MOLECULAR BEAM EPITAXY.** A.J. Peck, V.A. Stoina, I. 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. These relaxation times are correlated with temperature dependent Hall and photoluminescence measurements. Results of spectral and frequency-dependent photoconductivity measurements are expected to provide information about the valence band structure of these GaN samples. These mechanisms appear to rely on carrier trapping. Photocarrier measurements have been performed to investigate the electrical nature of the capture centers. This work was supported by ONR Grant N00014-96-1-0088 and monitored by Colin E. C. Wood.

**W11.16**

**THE USE OF MICRO-RAMAN SPECTROSCOPY TO MONITOR HIGH-PRESSURE HIGH-TEMPERATURE ANNEALING OF Mg-DOPED GaN FILMS.** M. Kuhal, J. M. Haynes, H. Wills Physics Laboratory, University of Bristol, Bristol, UNITED KINGDOM; J. Jun, T. Sasaki, UNIPRESS, Polish Academy of Science, Warsaw, POLAND; H.H. Tse, J. S. Williams, R.C. Jagadish, Department of Electronic Materials and Engineering, The Australian National University, Canberra, AUSTRALIA.

We have investigated the high-pressure high-temperature annealing of Mg-doped GaN films. The structural quality, the free carrier concentration and the strain in the implanted GaN films were monitored nondestructively 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 40-200 nm thick 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 Mg-doped GaN film. Mg-P+ implanted GaN films were annealed up to temperatures of 1500°C under nitrogen overpressures up to 1.6 GPa. We find the non-stoichiometry recovery of their crystalline quality at 1400-1500°C. The high nitrogen overpressures prove very effective in preventing oxygen 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 monitored by Raman 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 in-field free-carrier concentration increase at annealing 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. Bunes, W.D. Herzog, M.S. Unlu, 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 and time-resolved TRPL (time-resolved photoluminescence) experiments, in particular, are powerful tools to study these systems because the temporal information combined with the spectral data can help determine the dynamics of the carriers involved in the optical processes. One aspect of the 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 (~5x10^{17} cm^{-3}), low temperature time-integrated PL spectra identified the free exciton and bound exciton peaks. The former peak was observed at ~200 meV below the free exciton peak. The radiative recombination lifetimes were found to vary from 500 ps for FX and 350 ps for DX in the middle of the sample to 150 ps for FX and 350 ps for DX 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 dislocation 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. Gölker, A. Hoffmann, and I. Brener, 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 become a major 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 wurtzite GaN. By using optical reflectance measurements the structures of free exciton states of GaN-hypers 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) dielectric 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 and transversal splitting of the exciton and the value of this splitting is directly correlated to the oscillator strength of the resonances. Moreover, we use a further experimental method to investigate the oscillator strength: the calorimetric absorption spectroscopy (CAS). This method can detect directly the retroreflection of the crystal which dominates the lifetime of the respective resonances and therefore, their oscillator strengths. Furthermore, quantum efficiency 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%.


In this work, the optical properties of AlGaN thin films grown metalorganic vapor phase epitaxy (MOVPE) have been characterized by a guided-waves technique based on the prism coupling. The reported results demonstrated the usefulness and the accuracy of such a method for simultaneously determining the film thickness and the refractive index. The previous values of the refractive indices (n) and their dependence on the alloys composition (x) were reported for AlGaN systems. A relationship was therefore established. Moreover, the composition of the alloys could be accurately obtained using optical measurements at a single wavelength between 420 nm and 750 nm. In order to analyze the homogeneity of the films and the film-substrate interface, we have reconstructed the refractive index profiles directly from the knowledge of the optical properties. In some cases, we have observed essential changes in the index profiles attributable 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 35%.

W11.50 DEEP LEVEL RELATED YELLOW LUMINESCENCE IN n-TYPE GaN GROWN BY MBE. Christian Rieger, Giancarlo Salvetti, Carlo Zanotti-Fregonara, CNR-MASP Inc., Dept. of Physical and Structural Properties of Electronic Materials, Parma, ITALY; Enos Gambin, CNR-MASSPEC Inc., Dept. of Physics of Semiconductors, Parma, ITALY; Martin Albrecht, Ernst Strüng, Ernst Strüng, Parma, ITALY; Markus Meyer, Markus Kemp, Ulm Univ., Electronics Dept., Ulm, GERMANY.

The broad yellow emission (YL) in n-type GaN grown p-type GaN layers doped with Mg concentrations ranging from 10^{16} to 10^{19} cm^{-3} was studied by spectral CL (Ts5k), 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, 3.27 [2H-IX] and 3.46 [2H-IX] eV. TEM evidenced a cubic phase whose amount increased by increasing the Mg concentration in the layers. By applying the layer/substrate interface, nano tubes with diameter of 3x10^{-1} cm^{-3} were observed. Besides thin, 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_{2}+V_{C} complex; the 3.27 eV emission was ascribed to a shallow acceptor at about 220 meV above the VB due to Mg_{2}. 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 0.81 eV below the CB edge due to Mg_{2} and the shallow acceptor due to Mg_{2}. This assumption was checked by studying the role of C in the Mg compensation. CL spectra from an heavily C contaminated sample showed transitions between a deep level at 600 meV below the CB and a deep acceptor level at about 0.91 eV above the VB due to a N_{2}+V_{C} 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 PHOTOEMISSON SPECTROSCOPY. Abigail M. Beeson, 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 Haynes, 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 ambient temperatures. 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, nitrogen and water vapour, nitrogen and argon] at different temperatures. The region in the PL between 2.0 eV and 2.8 eV which contains the peak commonly referred to as Yellow Luminescence was studied. In this study peaks appeared at approximately 2.3-2.5 and 2.8 eV, some what higher than the usual third yellow luminescence peak. We find that the 2.0-2.8 eV peak is dominant for high annealing temperatures and that the 2.3-2.5 eV peak dominates at lower temperatures. The sample 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.

In spite of a large lattice mismatch (15%) between GaN and sapphire, the use of a low temperature buffer layer makes it possible to grow device-quality GaN layers by MOVCD. In this report we present experimental results concerning the 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 (OPO) 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-axis 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 relation to the incident fundamental beam. Five oscillation-like Fabry-Pérot modes were observed in measured SHG and THG angular dependences. The effective values of non-linear optical susceptibility coefficients for GaN layers were estimated in the context of the z-cut quartz. The obtained results are explained taking into account the contribution of two GaN films polarization microstructures and residual strain to the non-linear optical response.

FATIGUE RECOMBINATION BETWEEN TWO DIMENSIONAL ELECTRON GAS AND PHOTOCREATED HOLES IN MODULATION DOPED AlGaN/GaN HETEROSTRUCTURES.

The photoclinence (PL) related to the recombination of two dimensional electron gas (2DEG) in AlGaN/GaN heterostructures has been studied extensively, which is denoted in the B-band. The B-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 recently. 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 mole fraction in the AlGaN layer is 0.15. The concentration of the electron beam was driven by a thin AlGaN layer with the Al mole fraction of 0.07. The GaN layer suppressed the diffusion of photocreated holes. The PL peak related to the recombination between the 2DEG and photocreated holes at the heterointerfaces is located at 3.480 eV at 40 K, which is 45.2 meV lower than that of the free exciton (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 hot electrons on the bending of the conduction band at the heterointerface increases as temperature or the excitation intensity is increased.

SPECTROSCOPIC ELLIPSOMETRY: ANALYSIS OF InGaN/GaN AND AlGaN/GaN HETEROSTRUCTURES USING A PARAMETRIC DIELECTRIC FUNCTION MODEL. J. Wagner, A. Ramakrishnan, H. Okloh, M. Kuner, K. Kochler, Fraunhofer-Institut fuer Angewandte Festkoerperforschung, Freiburg, Germany; B. Jobs, J. A. Woollam Co., Inc., Lincoln, NE.

Reproducible growth of high-quality [AlGaN]N heterostructures requires, because of the rather narrow growth parameter window, fast and efficient in situ characterization of, e.g., composition, strain, and optical properties. 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 MOCVD growth processes. Growth rates of 600 Å/min SE has been used for so far only to study bulk-like GaN, AlGaN, and InGaN layers [1]. The aim of the present investigation was to apply variable angle SE to the characterization of GaN/AlGaN/GaN heterointerfaces and to investigate InGaN/GaN quantum well structures. 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 GaN/InGaN/GaAs the fundamental gap band gap resonance of the InGaN was found to broaden for QW widths around 10 nm, as compared to bulklike 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 modeling and quantitative analysis of the pseudodielectric function spectra of complete LED and laserwave structures.


FIESECONDS PHOTON-INDUCED REFLECTIVITY STUDIES OF GaN PREPARED BY LATERAL EPITAXIAL OVERGROWTH. M. Waldauf, 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 photocreated change in reflectivity on a picosecond time scale. The sample employed in this study was a ~5 μm-thick undoped GaN LEO film grown by MOVCD upon 15 μm-wide SiO2 stripes patterned with 3 μm windows between the stripes. The photoluminescence peak for the sample was at 3.27 eV (390 nm). Frequency-dependent photoluminescence and pump and probe measurements were performed using a tunable source of ultraviolet pulses of ~150 fs duration. In all cases a positive, pulse-width-limited rise in the change in probe reflectivity ΔR associated with pump-induced bleaching is observed at zero time delay. For excitation at 364.5 nm, the ΔR 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 ~100 μm in diameter, we find that 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 (~1 ps) decay becomes prominent as the excitation density is lowered to~1010 cm−2. When the carrier density is halved again, this decay disappears, suggesting that the screening of electron-hole plasma may be important in determining the initial relaxation process becomes faster than the thermal resolution of our experiment.

CORRELATION OF MID-GAP OPTICAL EMISSION AND MOBILITY DEGRADATION IN HOMEOTAXIAL GaN WITH IONIZED NITROGEN FLUX. A.P. Young, J.L. Brdik, Dept. of Electrical Engineering, Univ. of California, Santa Barbara, CA; Yoshiki Nomi, Dept. of Electrical and Electronic Engineering, The University of Tokushima, Tokushima, Japan; C.W. Ts, 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 homeotaxial growth under different nitrogen growth conditions. Specimens were grown via molecular beam epitaxy (MBE) on GaN/AlN 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/neutr al flux ratio to determine how N ions affect mid-gap luminescence. Ion deflector voltages of 0 V, 500 V, and 700 V yielded specimens. Hall mobilities of 3000, 500, and 640 cm²/V·sec, respectively. Low energy electron-excited luminescence (LEEL) spectroscopy in ultrahigh vacuum showed corresponding mid-gap emission intensities in the bulk (~3 eV incident) with the increase of defects in the growth column. The new results showed 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 GaN/InGaN/GaAs the fundamental gap band gap resonance of the InGaN was found to broaden for QW widths around 10 nm, as compared to bulklike 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 modeling and quantitative analysis of the pseudodielectric function spectra of complete LED and laserwave structures.
energy, 4 nm probe depth). The contrast in mid-gap vs. NB emission is significantly lower at depths below 30 nm, comparable to the penetration depth of IR radiation. A Co laser beam is used. NB emissions exhibit oscillations indicative of smooth interfaces, as confirmed by atomic force microscopy. LEEM spectral features alone demonstrate the primary role of native defects, not impurities, in the mid-gap emission. Furthermore, the correlation of mid-gap spectral emission with mobility indicates the dominant effect of such defects on overall transport properties.

W11.57

**DYNAMICS OF ANOMALOUS TEMPERATURE-INDUCED EMISSION SHIFT IN MoOx-D-GROWN [Al, In] GaN THIN FILMS**

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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 dependence in increased PL intensity suggested that the effective lifetime was enhanced in the temperature range showing the anomalous temperature-induced emission behavior, reflecting superior luminescent 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 tails caused by non-random inhomogeneous alloy potential variations enhanced with increasing Al content.

W11.58

**TIME-RESOLVED SPECTROSCOPY OF InGaN**

Milan Popovsich, Frederick Long, Rutgers University, Dept of Chemistry, Princeton, NJ; Chong Tran, EMCORE Corp., Sommese, NJ.

We have used time-resolved photoluminescence to examine InGaN-GaN light-emitting diodes (LEDs) before the final stages of the fabrication process. This result provides a new insight into the differences in the time-resolved kinetics between InGaN, GaN and super bright LEDs. The lifetime of the emission for the dim LED is quite short, 110 ± 20 ns at PL maximum, and the kinetics are not dependent upon temperature. In contrast, the longer lifetime of the superbright LEDs, the kinetics are clearly wavelength dependent, highly non-exponential, and are on the nanosecond time scale (lifetimes are in order of 1 μs for bright and 10 μs for super bright LED at the PL zone). Such long times are in agreement with the prediction of excitation 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. This result is attributed to the effects of nitrogen vacancy defects. 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 material. We have used the time-resolved photoluminescence to measure carrier diffusion in the p-type GaN region of the LED.

W11.59

**COLOR EMISION FROM GaN-CO-DEPONATED WITH Er2+ AND Eu3+ OR Tm3+. D.S. Lee, R. Birkhahn, M. Gatter, J. Heikenfeld, A. Steckel, Nanoelectronics Laboratory, University of Cincinnati, Ohio.**

Rare earth (RE) doped semiconductors have been studied because of their suitability for optoelectronic devices. Interest in doped RE GaN has increased to develop novel electroluminescence (EL) devices which combine the unique properties of GaN as a host material with the 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 low temperature emission from RE-doped GaN: Er2+ shows two green emission lines at 527 nm and 558 nm; Fe3+ shows red at 650 nm; Tm3+ shows blue at 480 nm; Eu3+ shows red at 620 nm and several minor lines. For this abstract, we present the mixed color emission of GaN films co-doped with Er3+ and Eu3+ and photoluminescence (PL) RE co-doped GaN films were grown by solid source MBE on Si (111) substrates using solid sources for GaN, Er, Eu and Tm. In a plasma glow discharge, the RE ions doped into the n-GaN films emit light in the visible (green and blue, respectively) corresponding to Er3+ and Tm3+ atomic transitions in the rare earth atom. Simple Shockley 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 Er3+ and Eu3+. PL measurements demonstrate that the relative intensity of the green emission of Er3+ increases linearly with Er3+ concentration using a fixed Eu3+ 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-ANNEAL-INDUCED ACTIVATION UP CONVERSION LUMINESCENCE FROM FIB-IMPLANTED GaN FILMS**

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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 ions have drawn the most interest because of the Er3+ emission at 1.54 μm and Pr3+ emission at 1.3 μm as they correspond to wavelength windows to minimize 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) and electroluminescence (EL) have been observed from GaN co-doped with Er, Eu, Dy, Er, and Tm doped GaN. This indicates that GaN is an excellent host for the incorporation of rare earth elements. We report growth upconversion luminescence from FIB-Implanted GaN films after annealing. We have investigated both furnace (FA) and rapid thermal (RTA) annealing under different ambient conditions at a temperature of 1100°C. We have studied the effect of proximity caps [SiO2, Al2O3], as well as encapsulation. For example, GaN samples at 1100°C for one hour exhibited strong green upconversion at 525 nm and 546 nm under red (840nm) and infrared (1.0 μm) excitation. Upconversion intensity was measured for Er3+ concentrations ranging from 4.9x1018 to 2.4x1019 atoms/cm3. Maximum upconversion intensity at 546 nm was observed at a dose of 1.2x1019 atoms/cm², which corresponds to an atomic percentage of 0.3-0.5%. RTA was used to minimize surface roughness while maintaining high performance. The upconversion spectra of FIB 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

**GaN AND Er SITE COMPETITION IN GaN:Er FILMS EXHIBITING VISIBLE LUMINESCENCE**


The recent discovery that GaN doped with Er emits visible as well as the usual infrared (1.54 μm) luminescence has prompted an investigation into the intrinsic limitations to this material. To further the understanding of both material 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 (infrared) luminescence involving RE f-states in GaN:Er (green), GaN:Er (red), GaN:Eu (blue) and GaN:Tm (red). All of these systems luminesce under both optical and electrical
pumping. The GaN:Er films were produced by MBIE with a nitrogen plasma source and solid sources for Ga and Er. Since the visible luminescence of 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. 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 concentration of Er incorporation below that the GaN films is controlled by not only the flux of Er but also the flux of Ga, indicative of site competition during growth.


An attractive alternative for 1.54 μm heterojunction semiconductor lasers are Er-doped semiconductors, whose emission wavelength is host-mismatch intensive. H3-nitrides are particularly attractive for this application as their wide bandgaps help to reduce thermal quenching of the Er3+ 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 H3-nitrides). The contribution of other impurities such as C and H is expected to play an important role in the emission process. In AIN, it has been shown that hydrogenation of Er-doped material was effective in increasing the 1.54 μm 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, we report the effect of H annealing on the luminescence intensity from Er-doped GaN and have been investigated by both rapid thermal annealing and annealing under an H2 plasma in UHV. Unlike AIN, 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 hydrogen effects of material codoping with H2 were reported in regard to both luminescence and the degree of thermal quenching.

**W11.65** CATHODOLUMINESCENCE SPECTROSCOPY OF EBURRUM DOPED GALLIUM NITRIDE GROWN ON SILICON BY MBIE AND MOME. 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 a laser active and amplifier in the 1.5 μm 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 the results have not yet been put to use because of low 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-on-silicon 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 ~2% by mass. For the MBE-grown GaN case, the carbon and oxygen impurity concentrations were 1-10 cm^-3, while the impurity level in the MOME-grown specimen was a factor of ten higher. We measured four excitation peaks in the LEEN spectra at 0.8, 1.8, 2.3, and 2.4 eV, in addition to the GaN near band edge 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 and the lattice location was determined using channeling Rutherford backscattering. Furthermore, the Er peak emission intensities increase with annealing by a factor of 12 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. MOME. 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.

**W11.66** PHOTOLUMINESCENCE AND CATHODOLUMINESCENCE OF GaN DOPED WITH Pr. W.M. Jedwabniak, L.J. Lozykowski, School of Electrical and Computer Engineering, Ohio University, Stocker Center, Athens, OH; I. Brown Lawrence Berkeley Laboratory, University of California at Berkeley, Berkeley, CA.

In this study, we investigated the cathodoluminescence (CL) and photoluminescence (PL) and their kinetics of GaN implanted with Pr by a pulsed laser. The GaN:Pr+ luminescence spectra as well as the kinetics were determined using LEEN of MBE and MBIE. A Pr:0.05% luminescence intensity is observed from the 800 nm to 1000 nm without emission from a GaN host. The rise and decay kinetics as a function of temperature were analyzed on a proposed model. The temperature dependence of the decay rates shows that relaxation occurs mainly by high energy phonon emission. The transition energies of Pr3+ 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 110 to 230 K. The results indicate that rare earth dopants like Pr are suitable as a material for visible optoelectronic devices.


The visible and infrared luminescence from rare earth doped GaN is of significant interest for potential applications in optical communications and full color displays. In this study, we report the relationship between the 413 nm, 537 nm, 568 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 MOBE and SSMBE. GaN:Er prepared by MOBE exhibits 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 this case, the 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.


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 these devices requires use of dry etch processes with relatively high ion energy in order to break the strong Ga-N bond (8.92 eV/amu), which causes some ion-induced damage and possibility of a non-stoichiometric near-surface region due to preferential loss of N. 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 Cl2/Ar Inductively Coupled Plasma (ICP) exposure on GaN Schottky diodes which reduces the presence of adverse damage. Exposure in Cl2/Ar discharges produces reductions in both reverse breakdown voltage (Vb) of Schottky barrier height (φb).

The extent of these reduction is a function of both ion energy and ion flux. Two-day (150 s) etch treatments were performed in an attempt to remove the ion-damaged GaN surface layer, namely annealing in N2 or UV-ozone oxidation followed by dissolution of the oxide. We investigate the effects of UV ozone time, anneal temperature, and HCl concentration on Si etch rate. We found that ~40% recovery in Vb and ~20% in φb for the UV ozone time up to 5 min, but there is no further improvement for longer time. For the annular temperature, there is ~50% recovery in Vb for anneal temperatures of 500-500°C, but little change for higher temperatures. The improvement in both parameters (Vb and φb) leads to saturation beyond 60 sec. Use of a stronger HCl solution (~38%) also improves the BD value compared to use of the 120 solution. All treatments provide primarily 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.

**W11.07**  
PRODUCTION AND DEVICE PERFORMANCE OF GaN POWER RECTIFIERS X. A. Chu, S. J. Pearson, University of Florida, Department of Materials Science and Engineering, Gainesville, FL; G.T. Deng, A.P. Zhang, F. Ren, University of Florida, Department of Chemical Engineering, Gainesville, FL; J. Han, Sandin National Laboratory, Golden, NM; J.M. Lee, C.-C. Chu, 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 (5-11 mm 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$_{BR}$/R$_{ON}$ of >4.5 MW/cm$^2$ were achieved at 25°C. Values of blocking voltage to forward voltage drop of >1000 were obtained. The V$_{BR}$ values for GaN are still about a factor of 2 lower than predicted theoretically for the doping and layer thickness used. A comparison of different device termination techniques (implant, dielectric passivation, guard-ring) for improving V$_{BR}$ and the resultant effect on the temperature coefficient for V$_{BR}$ will be presented.

**W11.08**  
OXYGEN IMPLANT ISOLATION OF n-GaN FIELD-EFFECT TRANSISTOR STRUCTURES. G. Deng (1), X. A. Chu (2), P. Ren (1), S.J. Pearson (1), J. Han (3), A.G. Bialas (4) and R.J. Shull (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=10$^8$ cm$^{-3}$, 3000 Å thick) to be a very viable method for device isolation. GaN based devices have 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 n-implanted sheet resistance of 41Ω $^{-2}$/sq. This is the best-reported sheet resistance value for GaN devices and is comparable to isolated GaN on Sapphire. We have produced thermally stable material as well. The sheet resistance remains above 10$^5$ $\Omega$ at annealing temperatures of 600°C. SIMS analysis was performed and no diffusion of the implanted oxygen was observed for any anneal temperature of 1000°C. Device isolation holds up well at high temperatures, where future state-of-the-art GaN devices are envisioned to operate and excel at.

**W11.09**  
DEVELOPMENT OF SiDIE BANDGAP SEMICONDUCTOR PHOTONIC DEVICE STRUCTURES BY EXCIMER LASER MICROJAMACHING. Qing Zhou, Gregory W. Auner, Je Xu, Wayne State University, Dept. of Electrical and Computer Engineering, Detroit, MI; Rattan Nakk and P.K. Kuo, Wayne State University, Dept. of Physics, Detroit, MI.

AlN films were grown on Si(111), Al$_2$O$_3$(0001), and Al$_2$O$_3$(1102) substrates by plasma source molecular beam epitaxy (PSMBE). Structural characterization of the film was performed by x-ray diffraction (XRD), x-ray high energy electron diffraction (RHEED), and high energy electron microscope (HREM). The XRD pattern indicates complete film texture. Cross-sectional TEM reveals epitaxy of AlN on these substrates. The Al$_2$O$_3$(0001) and Si(111) phase is lattice matched to the cubic growth of AlN and the Al$_2$O$_3$(1102) phase is lattice matched to the tetrahedral 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 clear precision machining of AlN with high aspect ratio and straight walls (isotropic etch). 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 pair of UV imaging sensors structures will be presented.

**W11.10**  
GaN ETCH RATE DEPENDENCE ON ION BOMBARDMENT IN AZ-400K. C.A. Crenelly, Naval Research Laboratory, Washington, DC; B. Moir, Novex Research, INC., Alexandria, S. Schiester, George Washington University, Washington, DC.

Selective wet etching is an important technique for device manufacturing. The AZ-400K photoreactive 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 composition is very high in AO-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 Si substrates by MOCVD or MSE technique. Parts of the GaN layers were implanted using different implantation parameters. The etching experiments were performed in AZ-400K solutions RT and 80C. The locally damaged GaN shows high etch rates in AZ-400K. The etch rate and the ion dose play a significant role in the change of GaN etch rate. The change of GaN etch rate seems to be related to the ion damaged layer induced 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.


**W11.11**  

The oxidation of GaN epilayers in dry oxygen has been investigated. The GaN epilayers, about 1 μm thick, are grown on [0001] sapphire substrates by Rapid-Therm Process/Low Pressure Metalorganic Chemical Vapor Deposition. The GaN epilayers are placed in dry oxygen at different temperatures for different time. The 0.2θ scan X-ray diffraction (XRD) spectroscopy is used to characterize the process of oxidation. XRD data show that the oxidation of GaN begins at about 650°C. When the GaN are oxidized at 800°C, the XRD data is not available for this temperature. The oxidation product of GaN is Ga$_3$O$_5$. The Ga$_3$O$_5$ diffraction peaks appear at 1850°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 oxide peak is at 1132, which is followed by 306. For investigating the oxidation kinetics, the measured intensity of the 1132 peak is used 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 lower temperatures. Therefore, the oxidation rate at 900°C, the oxidation rate is very fast, which is considered as the results of the GaN decomposition at high temperature under atmosphere.

**W11.72**  

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 temperatures below 1000 °C. Annealing at higher temperatures is extremely difficult and only partially successful due to the severe surface dissociation. As a result, optimum electrical activation is a challenge in GaN, requiring the use of 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 800 nm. Implantation as hydrogen is chosen for most detailed study since such a light species introduces dike, discrete damage, ideal for PL. However Si-implanted GaN films also been studied. Results show that implantation results in a degradation of band-edge luminescence with increasing ion dose. Removal of damage with annealing has not been found to recover. For H implantation at doses of <10$^6$ 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 grown in other luminescent centres present in the starting GaN material.
Photoluminescence (PL) was used to study the surface damage produced by photo-electrochemical (PEC) etching GaN with KOH electrolyte. In the etching process, OH- prefer to take away gallium atoms through the thin damage layer with complex defects of Ga vacancy bond oxygen in nitride site was formed. The surface defect create a broad yellow luminescence (YL) peak centered at 2 eV 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 (1110) 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-grown GaN was found. The composition of PEC etching with and without post-treatment by the boiled KOH was also studied by auger electron spectrometer (AES) depth profile. The etching surface have similar composition with as-grown surface. A new damage free etching process evidenced by YL reduction and AES were revealed in this paper.

**W1.16**
**HIGHLY CHEMICAL REACTIVE ION ETCHING OF GALLIUM NITRIDE AND ITS INFLUENCE ON SCHOTTKY CONTACTS.**
**Found Karoutz, Bart Jacobs, Eindhoven Univ of Technology, Faculty of Electrical Engineering, Div TIE, NETHERLANDS; Ingrid Moerman, Koen Jacobs, INTEC, Univ of Ghent, BELGIUM; Jan Heyder, Sylvester Pavlus, High Pressure Research Center, Polish Academy of Sciences, Warsaw; Carol Hofstra, Karel Rie, Herman Begeman, Katholieke Univ Nijmegen, NL, 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 GaN and InP based transistors by using wet chemical etching. This is not valid for GaN based structures as dry etching techniques is required for processing electronic devices. In this work we present a novel chemistry for RIE of GaN based on SiCl₄:Ar :SF₆. This gas combination allows high etching rate at relatively low DC bias, for instance, at an RF power of 150 W, an etch rate of 15-20 nm/min can be achieved on GaN smooth surface (DC bias of 300 V). Assuming that the physical sputtering is the dominating etch component, the RIE process yield is estimated to 90%. In the perspective of using GaN substrates for homogeneity of high quality GaN active layers, we have studied the above described RIE process to smooth Gas-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 Non-polar GaN resulted in a higher etch rate than Gas-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. These were made on non-polar GaN (0001) faces) 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 4 X 10⁻⁴ A/mm (20 V), 1.12 (as grown) and 1 X 10⁻⁴ A/mm, 1.12 (after RIE, etc.). Based on these results we claim the feasibility of gas-assisted AlGaN HEMTs.

**W1.27**
**IMPROVED LOW RESISTANCE CONTACTS OF NI/Au AND Pd/Au TO p-TYPE GaN USING A CHROMOGENIC TREATMENT.**
M.Hun 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 devices. Such contacts have been made using Ni/Au and Pd/Au contacts to p-type Mg-doped GaN (3 x 10¹⁷ 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 N₂ which reduced the specific contact resistance from the range of 9.46 x 10⁻⁵ Ω cm² to 2.96 x 10⁻⁶ Ω cm² for Ni/Au and from the range of 8.35 x 5.01 x 10⁻⁴ Ω cm² to 4 x 2.1 x 10⁻⁴ Ω cm² 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 met allurgy of Ohmic contact formation.
Galide-forming metal) scheme for p-GaN, which utilizes the fact that metals could be classified according to the enthalpy of compound formation into galide-forming, nitride-forming and neutral groups. Under the proper conditions, similar 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 in p-GaN/Au. These results were confirmed on 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. The results of the most promising materials are electron traps with high activation energies of 0.66 eV and 0.86 eV. The density of all electron traps was very much lower in Ni-Ga annealed 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 density. This was further confirmed by the fact that the diffusion length values could be varied in a wide range (from 0.4 μm to 2 μm) for Ni-Ga annealed films without any obvious changes occurring to the density of DETS traps. Persistent photocapacitance measurements on various samples show that 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 DETS and of potential fluctuations in the samples will be discussed.

W11.80 PHOTOCAPACITANCE STUDY OF DEEP LEVELS IN MOCVD-GROWN N-GaN. Adrian Herren, Dae-Won 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 on sapphire substrates by metal organic chemical vapor deposition (MOCVD). Unintentionally doped 1.35 μm-thick n-type layer (~5×10^17 cm^-3) with a threading dislocation density of ~10^10 cm^-2 was grown on heavily doped n-type buffer layers, followed by a 1500 A-thick Mg-doped p-type GaN cap layer. Front ohmic contacts were fabricated by depositing 1 μm-thick Ti/Al/Ni/Au films. The diode size was 0.25 mm^2, and excellent rectifying behavior was obtained with a turn-on voltage of ~2.2 V and leakage current below 6.5×10^-8 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 mercury lamp as light sources and the measurements were observed at 1.5, 2.6, and 3.22 eV from the conduction band with concentrations in the 10^12 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 growth flaws 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. Poyhokov, N.B. Smirnov, A.V. Gvoresh, Institute of Rare Metals, Moscow, Russia; A.S. Uskov, N.M. Shmidt, B.V. Pushnay, D.V. Tvetkov, S.I. Stepanov, A.F. Ioffe Physico-Technical Institute, St. Petersburg, Russia; V.A. Dmitriev, TDI, Inc., Gaithersburg, MD.

A set of undoped and lightly Mg doped GaN films were grown by MOCVD on sulphur-doped AIGaN 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 IRXRD, MCL spectra measurements, MCL and EHC imaging. Diffusion lengths of minority carriers in Mg doped AIGaN/GaN structures measured in Ni/Ti/Au contact to p-GaN after an anneal at 300°C for 5 min made the ohmic contact schemes to p-GaN have been evaluated. The results of the most promising materials are electron traps with high activation energies of 0.66 eV and 0.86 eV. The density of all electron traps was very much lower in Ni-Ga annealed 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 density. This was further confirmed by the fact that the diffusion length values could be varied in a wide range (from 0.4 μm to 2 μm) for Ni-Ga annealed films without any obvious changes occurring to the density of DETS traps. Persistent photocapacitance measurements on various samples show that 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 DETS 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. Weite, A. Kracht, M. Läker, D. Rudloff, J. Krienert, M. Krawitz, Institute of Experimental Physics, Otto-von-Guericke-University Magdeburg, Magdeburg, Germany; W. Schottky Institute, Technical University Munich, Garching, Germany.

Deep defect levels were characterized in gallium nitride layers grown by molecular beam epitaxy (MBE) and by metalorganic vapor phase epitaxy (MOVPE) using thermal admittance spectroscopy (TAS) [200 MHz-1MHz] and low temperature transient capacitance (LDLTS, with modulation frequencies of 1kHz - 100kHz]. Persistent 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 decreasing low frequencies. LDLTS electron traps with thermal activation energies of 0.17eV (0.2-0.26eV), and 0.6eV were identified which are well known from the literature. In contrast to those LDLTS results, probing the whole depth of the space charge region, only one defect type 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 (210-260) 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 state density as well as the bulk 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 the experimental techniques (DLTS, LDLTS, and TAS) give identical results.


The defect levels associated with Mg doping concentration in n-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 level located at 3.0 and 14.0 meV above valence band in as grown samples. But, in thermal annealed samples, PC spectra exhibited various additional peaks depending on the annealing treatment. For the heavily Mg doped samples (6-7×10^17 cm^-3), we 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 3×10^17 cm^-3, additional peak on the low energy side was observed at ~9.6 eV. This peak is related to the Ga vacancy located at ~980 meV above valence
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 0.34 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 E1, E2, and E3, have been observed. A1, with an activation energy of 0.83 eV and concentrations of mid-1015 to low-1016 cm−3, is a dominant center in RMBE-GaN layers. C1, 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, E1, with an activation energy of 0.25 eV and an apparent cross section of 3 x 1010 cm−2, shows a close connection with the AFR, i.e., E1 could be clearly observed only at a low AFR. Based on a comparison between traps E1 and E (the latter was observed in n-GaN layers, grown by both MOCVD and HVPE, after 1-MeV electron-irradiation), we believe that E1 is a defect complex involving the nitrogen vacancy.

W11.87

We have used deep level transient spectroscopy (DLTS) to investigate the electrical properties of two defects introduced in n-GaN after Schottky contacts at Au Schottky contacts. The two traps, identified as E2L and E2H, located at Ec - 0.22 ± 0.02 eV and Ec - 0.30 ± 0.02 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 introduced during annealing at temperatures of 100 K - 125 K and 115 K - 140 K, respectively. The electric field enhanced emission from these defects indicates that the defects can exist in three charge states: as a positively charged donor, a neutral state as well as a negatively charged donor. The work shows 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: Bruce J. Skromme
Friday Morning Session, December 3, 1999
Room 302 (H)

8:30 AM W12.1
GROWTH OF InGaN/GaN NANOSTRUCTURES FOR VCSELs AND QUANTUM DOT LASERS. Yasuyoshi Arakawa and Takuo Soma, 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 Al0.63Ga0.37N layers was grown on a (0001) sapphire substrate by atmospheric-pressure MOCVD. Then, a 2.5 μm cavity comprising 26 periods of In0.35Ga0.65N quantum well layers was grown on the nitride DBR. Finally, a reflector consisting of 15 periods of ZrO2/SiO2 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 395 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 x 1010 cm−2 with the minimal diameter of 9 nm. Extremely sharp luminescence lines from individual localized states of the QD structures were observed by microphotoluminescence measurements. The successful growth and applications of InGaN/GaN QD lasers (161nm) led to the first lasing action in InGaN QD lasers at room temperature by optical pumping.

9:00 AM W12.2
CONTROL OFFORMATION SITES OF SELF-ASSEMLING GaN DOTS BY FOCUSED ELECTRON BEAM EXPOSURE. Koji Kamiyama1,2,3, Daisuke Yamazaki1, Kazuo Tsuda1 and Yoshinori Asahi1,2,3 Tokyo Inst. of Tech1, Interdisciplinary Grad
For realization of the quantum logic gates such as 'quibit' 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 candidates for the realization because of rather insensitive 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 rate of the quantum dots is successfully controlled by a focused electron beam. After chemical treatments of a Gr/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, N/P growth gas was inserted and the sample was annealed similarly 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 nucleation 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 W12.5
FOCUSED-ION-BEAM ETCHING OF NANOGATE-RIZE SIZE GaN/AlGaN DEVICE STRUCTURES AND THEIR OPTICAL CHARACTERIZATION BY MICRO-PHOTOLUMINESCENCE/ RAMAN MAPPING. M. Kuball, M. Benyoussef, H.-W. Man, Physics Laboratory, University of Heidelberg, Heidelberg, F. H. Morrisey, Philips Electronics 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 fabrication by microphotoluminescence/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 ultrasmall electronic and optoelectronic 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/Al0.15Ga0.85N HFET device structures were micro-machined using a FEI 2010 focused ion beam system. Gallium ion beam currents of up to 10 nA are used to select small pillars as small as 20nm in diameter from the HFET structures. Microphotoluminescence and UV micro-Raman maps were recorded from the HFET etched pattern using a Renishaw RM1000 UV-Raman system. Photoluminescence was detected from the nanometer-size GaN/Al0.15Ga0.85N HFET structures, i.e., from the Al0.15Ga0.85N layers in the device structure, despite the induced etch damage. The spatial distribution of GaN and AlGaN in the FIB-etched pattern was mapped using UV Micro-Raman spectroscopy. Photoluminescence was detected from the nanometer-size GaN/Al0.15Ga0.85N HFET structures, i.e., from the Al0.15Ga0.85N layers in the device structure, despite the induced etch damage. The spatial distribution of GaN and AlGaN in the FIB-etched pattern was mapped using UV Micro-Raman spectroscopy. Photoluminescence was detected from the nanometer-size GaN/Al0.15Ga0.85N HFET structures, i.e., from the Al0.15Ga0.85N layers in the device structure, despite the induced etch damage. The spatial distribution of GaN and AlGaN in the FIB-etched pattern was mapped using UV Micro-Raman spectroscopy.

10:30 AM W12.6
EVIDENCE FOR SPONTANEOUS POLARIZATION EFFECTS IN GaN/AlGaN QUANTUM WELLS. J. Simon, R. Langer, A. Bursi, N.-P. T. Pekeler, Direction de Recherche Fondamentale sur la Matière Condensée, CEA/Grenoble, Grenoble, FRANCE.

In wurtzite non-growing nitride heterostructures, in addition to piezoelectric effects, one expects a significant amount of spontaneous polarization (SP) effects, both generating large electric fields. Even though several groups have reported the existence of such fields, still, it has not been established experimentally whether SP effects play 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_A varying from 7 to 34%. The samples are grown by molecular beam epitaxy and they typically consist of 20, 40 and 60Å-thick single QWs separated by 100Å AlGaN barriers. X-ray diffraction experiments allowed to measure directly on each sample X_A and confirmed the excellent pseudomorphic quality on the substrate. In T=2K photoluminescence (PL) experiments, we observed strong PL shifts of the QW emission with increasing QW thickness and with respect to the GaN gap. This is a clear manifestation of an electric field F present in the QW. We measured F for all samples by fitting the experimental e1Δt 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 $F = \Delta P / \delta_x$, $\Delta P = L_y (L_y + L_z)$, where $L_y$ (L_z) is the total QW (barrier) thickness, and $\Delta P$ is the difference of the total polarization between QW and barrier layers, we determine $\Delta P$ in each sample and verify that it depends linearly on $X_A$. Furthermore, we compared $\Delta P$ with the piezoelectric polarization difference $\Delta P_{PE}$ estimated using available piezoelectric coefficients, and found that for all samples $\Delta P / \Delta P_{PE}$ is significantly over 1. This clearly suggests a non-piezoelectric contribution to $\Delta P$, which we interpret in 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. Anna Lisa Mazzola, Massimo Lazzaro, Giacomo Traversa, Roberto Capechi, Alessandro Longhi, Andrea Botchkarev, Hidde Meijer, Univ of Cagliari, INFN-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 of the QWs has been seen 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 2-4nm) in order to clarify the role of strain, structural parameters and built-in field in determining the well-width dependence of 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 a full self-consistent Tight-Binding model. The comparison between theory and experiment reveals that the spontaneous polarization field dominates 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 OF STUDY OF STRUCTURAL AND OPTICAL PROPERTIES OF In_Ga_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 InGaN$_x$N/GaN multiple quantum wells (MQWs) with different 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, 340, and 600 meV, 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 SE period (possibly caused by intermixing and/or well size irregularity) and for the fluctuation of alloy composition can be argued to be the responsible mechanism of broadening. These results indicate the determination of interface quality due to the difficulty of uniform 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 overcome the drawbacks associated with interface imperfection.

11:15 AM W12.8 EMISION AT 290 NM FROM GaN QUANTUM WELLS GROWN BY MOVCVD. Takahiro Someya, Katsuyuki Hashino, Janet Harris, Koichi Tsuchihashi, Satoshi Kako and Yasuhiko Arakawa.

We have measured photoluminescence spectra at 77 K from 1.5-nm-thick GaN quantum wells with Al$_x$GaN$_{1-x}$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 well, 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$_x$GaN$_{1-x}$N barrier layers up to 0.5. Spectral linewidth was 300 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 ultraviolet detectors, telecommunication devices at 1.5 μm 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. Stützler, R. Weisensorn, 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 the specific isotope 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 we used ion implantation with a dose of $3 \times 10^{15}$ cm$^{-2}$ with radioactive isotopes $^{75}$As and $^{76}$Se as the on-line mass separator facility ISOLDE at CERN. The implantation damage was removed by annealing the sample at 1273 K under N$_2$ atmosphere. The isotope $^{75}$As (half-life 64.28 h) decays into $^{75}$Ge (11.43 d) which finally transmutes into stable $^{75}$Ga. The isotope $^{76}$Se decays via $^{76}$As (26 h) into stable $^{76}$Ge. This chemical transmutation were monitored with PL spectroscopy with a half-life of 4.2 K. The PL spectra recorded within 30 days after implantation will be presented. The results will be compared with the PL spectra recorded within 48 h after implantation. Finally our PL data for the optical transitions at 2.58 eV (As), 3.38 eV (Ge), and 1.49 eV (Se) are in excellent agreement with the half-lives of the isotopes. This correlation also shows that each of these luminescence centres is contributed by exactly one As, Ge or Se atom.