SYMPOSIUM E
GaN, AlN, InN, and Their Alloys

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* Invited paper
Structural defects affecting the lifetime of GaN-based laser diodes (LDs) on epiretinue overgrown (EOL) GaN layers have been investigated. Almost all of the threading dislocations that appeared in the wing regions have edge character, whereas the dislocations at the coalescence boundaries have both edge character and mixed character. The origin of the decreasing dislocations in the wing regions are the lateral extension of dislocations from the seed regions that contingently bend upwards to the epi-surface. Comparing short-lived LDs and long-lived LDs that had almost the same power consumption, we found that the relative levels of dislocation densities in their respective active layers were different. In the degraded LDs, neither dislocation multiplication from the threading dislocations nor any structural changes of the threading dislocations were observed. This indicates that degradation is not caused by dislocation multiplication at the active layers, which is usually observed in LDs featuring zinc-blende-based structures. Although the threading dislocations in the LD stripes do not multiply during device operation, our degradation experiments revealed that the lifetime of the GaN-based LDs depends on the dislocation density. The degradation rate was almost proportional to the square root of the aging time. Our results indicate that degradation is governed by a diffusion process, and a detailed degradation mechanism is proposed.

9:00 AM E1.2

In the last decade, AlGaN-based laser diodes have been the subject of extensive research and development particularly for applications such as high density optical storage, e.g. Blu-ray. Since the first demonstration of a laser diode by Nichnich Corporation [1], the field has been dominated by the Metal Organic Chemical Vapour Deposition (MOCVD) epitaxial growth technique. The alternative growth method of Molecular Beam Epitaxy (MBE) has recently been shown to be competitive [2] despite the efforts of many research groups worldwide. MBE presents many potential advantages over MOCVD such as lower source material consumption, high purity material, in-situ growth monitoring. In June 2004 we reported the first InGaN quantum well laser diode grown by MBE [2]. The structures were grown on commercially available GaN template substrates consisting of 100 μm Si doped thick GaN deposited on a sapphire substrate by MOVCD. The threshold current density (Jth) of the devices was 30 kA/cm2. This relatively high Jth was attributed to the rough and non-vertical nature of the mirror facets formed using a plasma etching technique. The threshold current density of these first devices was too high to achieve continuous-wave (CW) operation. We have therefore focused on decreasing Jth and will report on the results and improvements which have been made. The threshold current density was reduced by growing lasers on commercially available free-standing GaN substrates. These substrates have around 100 times lower threading dislocation density compared to the template substrates previously used [2]. Index guided laser bars were fabricated using Electron Cyclotron Resonance (ECR) plasma etched ridge waveguide, cleaved facets and SO2/SiN4 high reflective facet coating. With this approach we have reduced the threshold current density to less than 15kA/cm2 and further progress in device performance will be reported [1]. [1] Yamada, J. Appl. Phys. 35, L74-L76 (1996). [2] S.E. Hooper, M. Kauer, V. Bousquet, K. Johnson, J.M. Barnes, J. Heffernan, Elect. Lett. 40, p.33 (2004).
The early efforts on developing AlGaN-based deep-ultraviolet light-emitting diodes (UVLeds) focused on improving material quality of AlGaN epilayers on sapphire substrates. The key technologies developed so far include the introduction of ultrahigh-quality thick AlN buffer layers, strain-induced quantum-well superlattices.[1, 2, 3] For the best effect, we recommend to grow these structures using Migration Enhance Metalorganic Chemical Vapor Deposition (MEMOCVD). Thanks to these technologies, multilayer quantum-well LEDs[4, 5, 6, 7, 8] further improvement on the deep-UV LED performance may interest in contributions from using thick AlGaN bulk materials as well as optimizing the multiple-quantum-well (MQW) active region. In this talk we report the MQW optimization experiments and discuss the impact on real 280 nm UV LED device performance. Competing effects such as strain-induced bandgap changes, spontaneous and piezoelectric polarization induced quantum confined Stark effects, carrier screening effects, and quantum confinement in irregularly shaped wells make theoretical predictions of the optimum well design difficult. In our experiments we found that the polarization induced quantum confined Stark effects in doped AlGaN MQW is negligible. For a doped MQW (Al0.49Ga0.51N/Al0.35Ga0.65N) with well width of 50 Å, the blueshift of the photoluminescence (PL) wavelength is within 1 nm when varying the excitation power density by more than 2 orders. Yet a five-fold PL enhancement was observed by reducing the quantum well width down to 25 Å, indicating confinement enhanced optical transition oscillation-strength by narrower quantum wells. The nature that carriers possess effective mass in high-Al-composition AlGaN materials requires very narrow quantum wells for efficient light emission. 280 nm UV LED device results will also be presented in the progress of the MQW optimization.

10:30 AM **E1.6**

**Fabrication of LED Based on III-V Nitride and its Applications.** Naoki Shibata, Optoelectronics, Technical Div., Toyota Gosei Co., Ltd., Nakashima-gun, Japan.

III-V nitride semiconductors had been expected to be suitable for LED with colors covering ultraviolet, blue, through green, and red with short wavelength. Both of the development of III-V nitride based LED and its applications are introduced. The MQW with GaInNAs, a well layer is used for our developed LED. Adjusting the “In” chemical content of the well layer can achieve the various wavelength of the LED including UV region, blue, green, and red. Our developed “short wavelength” LED (TG purple) with flip-chip structure has light output power of over 10 mW at 20 mA in bare chip condition. The wavelength of TG purple is around 385 nm and FWHM is less than 10 nm. One of applications of TG purple is the air purifier system which was developed by combining TG purple and photo-catalyst, which is TiO2. The photocatalyst is excited by the light from TG purple and decomposes the organic materials such as cigarette’s smoke. This system was equipped in a car and several applications of this system are expected in room air conditioners and refrigerators. Another major application of TG purple is a light source of white LED. There were many kinds of white LEDs. The first is white LED which combines blue LED and yellow phosphor. Although this white LED has high luminous intensity, the color rendering is not so good. This reason is because this white LED does not include red and green lights sufficiently in itself. The second is white LED which combined TG purple and blue, green, and red phosphors. The luminous intensity of this white LED is inferior to the former case, because relatively high energy loss exists when blue, green, and red lights are excited from phosphors by irradiation of TG purple. On the other hand, the red and green color rendering of this LED is superior to the former case. This is the reason why this white LED includes blue, green, and red light. It is pointed out that medium color rendering of this white LED is still not good compared with “sun light”. “TG True White Hi” utilized a combination of TG purple and new phosphor with broadband spectrum. The phosphors utilized in TG true white Hi is blue phosphor with peak wavelength of 450 nm, yellow phosphor with that of 575 nm and red phosphor with those of 615 nm and 630 nm. Color rendering index of “TG True White Hi” is over 90. This value is so high in comparison with that in the case of the white LED with blue LED and yellow phosphor. The luminous intensity of this white LED goes up to more than double by adding new phosphor with broadband spectrum to white LED based on TG purple. We continue to study the relationship between color index and luminous intensity by adjusting various phosphor combinations.

11:00 AM **E1.7**


The junction temperature of light-emitting diodes (LEDs) is a critical parameter that affects the internal quantum efficiency, maximum output power, and reliability of the devices. High-precision junction temperature measurement is reported for high-quality AlGaN LEDs emitting at 295 nm. The junction temperature is determined for a wide range of injection currents, based on the temperature dependence of the diode forward voltage. The measurement consists of a pulsed calibration measurement and a DC measurement. The junction temperature increases linearly with current from 21°C to 75°C as the DC current is increased from 0 mA to 50 mA. A thermal resistivity of 87 K/W is inferred from the measurement with the device mounted on a heat sink. In addition, a new expression for the temperature coefficient of the forward voltage is presented. The forward-voltage method is very sensitive and its accuracy is estimated to be ±0.3°C. The emission peak methods to measure the junction temperature are compared for comparison which is in good agreement with the forward-voltage method. The peak position of the spectra is influenced by alloy broadening, polarization, and quantum confined Stark effect thereby reducing the accuracy of these methods. The temperature measured by another method, the high energy slope is the carrier temperature, which is higher than the lattice temperature at the junction. This measurement is explored as a reference method.

11:15 AM **E1.8**


One of the most important issues in GaN-based materials and devices development that deserves greater attention is the effect of initial cleaning processes used on the surface of initial III-Nitride layers on the optoelectronic properties of the subsequent device structures deposited. We report here on the study of the effect of various cleaning processes applied to undoped GaN surfaces used for subsequent growth of LED structures. Chemical, optical and electrical properties of the surfaces of GaN and InGaN-based light-emitting diodes were systematically investigated by x-ray photoemission spectroscopy (XPS), Auger electron spectroscopy (AES), atomic force microscopy (AFM), temperature dependent photoluminescence and electroluminescence spectroscopy. Various cleaning procedures were used. These included different combinations of the following: trichloroethylene (TCE), acetone, methanol, DI water, HCl, and HF. Metallocorganic chemical vapor deposition was used to then grow epitaxial layer following the cleaning procedures. Initial surfaces of as-cleaned GaN layers were smooth with no observable change in roughness. Chemical species such as O and C were detected on the surfaces of all samples whereas F and Cl were detected only on the samples cleaned with HCl and with HCl and HF. The surface morphology of subsequently grown undoped GaN layers showed dramatically different properties in comparison those cleaned without HCl and HF and those with HCl and HF. Those cleaned with HCl and/or HF showed a high density of 3D structures and higher roughness as measured by AFM. Layers on the top surface of regrown LED structures suggest a 3D growth mode. LEDs grown on HCl and HF cleaned GaN template layer showed minimal photo- and electroluminescence intensity and failed in a short period of time in comparison with those without HCl and HF cleaning. We will also present a model that may explain the underlying phenomena leading to such dramatic changes in the optoelectronic properties of the LEDs stemming from the cleaning of the initial template layer.

11:30 AM **E1.9**

**Moth Eye Light-Emitting Diode.** Hideki Kasugai2, Yasuto Miyake3, Akira Honshio3, Takeshi Kawashima3, Kazuyoshi Inoue1, Kazuhiro Iwasa1, Satoshi Kawaiyama1, Hiroshi Amano1,2, and Isamu Miyake1,2.

Homogeneous optical properties of moth eyes are of great interest from both biological and technological points of view. A moth eye is a hierarchical optical bio-superstructure that consists of microscale and nanoscale roughness. The morphological characteristic of a moth eye is the result of the long-term evolutionary process to improve the optical performance. The optical performance of the moth eye is not only determined by the structural parameters of its surface, but also by the wavelength scale ranging from the visible to the infrared. We have recently developed a 3D-structured conical photodetector using the method of ion beam milling. The optical responses of the 3D-structured conical photodetector were examined using light illumination with various wavelengths. The results showed that the Moth eye structure had a strong dependence on the wavelength. Moreover, we have achieved a monolithic integrated photodetector, which has sub-wavelength ordered rough surface. A very low reflectance can be realized by forming two-dimensional periodic roughness with a period shorter than the optical wavelength.
forming triangular pyramid shapes with a mean period of approximately 100 nm and a mean height of approximately 400 nm. A period of 100 nm is shorter than the optical wavelength. The effect of "moth eye" structure on the light extraction is very significant. On the bottom of the SiC substrate. The "moth eye" structure was introduced on the backside of the SiC substrate using the CF$_4$-RIE technology. By using high-energy electron diffraction (RHEED), the surface is identified by a simple chemical treatment.

decreasing temperature, the aspect ratio remains almost constant at about 2 suggesting the QDs to have a well-defined shape. To clarify the impact of strain on the InGaN QD formation (i) the indium content was varied while keeping the growth temperature constant; and (ii) the dots were grown on AlGaN layers of different composition. On the other hand, the growth dynamics was investigated by (i) varying the InGaIn growth rate and (ii) introducing growth interruptions at various stages of the growth. The data is combined to decide how far the growth mode can be called Stranski-Krastanov like. Finally, InGaN QDs were buried by capping them with a thin GaN layer. The formation of the InGaN was found to decrease significantly due to the capping. A pronounced intermixing is proposed to take place which is studied by varying the growth temperature and the thickness of the capping layer.

2:30 PM E2.4
Growth and Characterization of Self-organized GaN Quantum Dots on Miscut (0001) Sapphire Substrates by Molecular Beam Epitaxy. Leo J. Schowalter, James S. Speck, Steven P. DenBaars, Shuji Nakamura; ERATO/JST UCSB Group, Santa Barbara, California. 3Materials Department, University of California, Santa Barbara, Santa Barbara, California. 4:00 PM E2.7

GaN quantum dots can be used as active layers in light emitting diodes due to quantum conﬁnement effects and temperature independent characteristics. The size distribution and dot density are important factors in determining the optical properties of such devices. In this paper, we report the growth and characterization of self-organized GaN quantum dots on a miscut (0001) sapphire substrate as a potential method to fabricate QDs. The QDs were formed by Stranski-Krastanov mode of growth in which strain is the driving force for the dot formation. Prior to the MBE growth, the sapphire substrates were annealed at characteristic temperatures to reveal the steps and the associated growth mode of epitaxy of quantum dots and characterized carefully by atomic force microscopy. To form GaN QDs, these substrates were first coated with 100 nm AlN films and followed by several monolayers of GaN. The growth and the capping of the QDs were monitored by RHEED. Atomic force microscopy studies show that the quantum dots are oriented along the steps of the sapphire substrate. The average size of GaN QDs was of 23 nm in diameter and 1 nm in height. The dot density was in the order of 10^{11} dots/cm^2. These dots are being investigated by transmission electron microscopy (TEM), PL, and CL measurements.

2:45 PM E2.5
Growth and Properties of Nonpolar a-plane InGaN/GaN Multiple Quantum Wells Grown on Reduced-Defect Lateral Epitaxially Overgrown a-plane GaN. Arpan Chakraborty, Stacia Keller, Benjamin A. Haskell, Feng Wu, Patrick Walterte, Salka Keller, James S. Speck, Steven P. DenBaars, Shuji Nakamura and Umesh K. Mishra; 1ECE, University of California, Santa Barbara, Santa Barbara, California. 2Materials Department, University of California, Santa Barbara, Santa Barbara, California.

In this study, we investigated the growth, structural and luminescence properties of nonpolar a-plane InGaN/GaN multiple quantum wells (MQWs) on reduced-defect lateral epitaxially overgrown (LEO) a-plane GaN. Investigation of nonpolar InGaN/GaN based materials have attracted great attention in the recent years because of polarization free heterostructures and its potential of improving the performance of (Al, Ga, In)N based optoelectronic devices. In comparison to c-plane InGaN/GaN MQWs, very little is known about the properties of nonpolar-a-plane InGaN/GaN MQWs. This is primarily because of poor optical properties of the planar a-plane (Al, Ga, In)N films due to high defect densities in these materials. 12 periods InGaN/GaN MQW samples were grown by metal organic chemical vapor deposition (MOCVD) on concurrently loaded hydride vapor phase epitaxy (PWHE). At high temperature, reactor pressure, and growth rate, on the composition and the room temperature photoluminescence (PL) properties were investigated. The properties of the non-polar a-plane MQWs were compared to those of c-plane InGaN/GaN MQWs. High resolution X-ray analysis revealed that the incorporation efficiency of indium in the a-plane quantum wells (QWs) was much lower compared to the c-plane QWs, grown under identical conditions. The intensity and the full width at half maximum (FWHM) of the nonpolar QWs luminescence signiﬁcantly improved upon lowering the reactor pressure. The PL intensity also improved upon lowering the growth rate at higher growth pressures. The effects of well width and barrier thickness on the luminescence properties were also investigated. The optimum barrier width of 11.5 nm for the a-plane MQWs was similar to those for c-plane MQWs but the optimum well width of 5 nm for a-plane was higher compared to the optimum c-plane well width. The results of Atomic force microscopy and Transmission electron microscopy will be presented at the conference.
are very limited. In this paper, we will report on a solubility study of GaN in a supercritical ammonia solution and characterization of GaN grown on a free-standing GaN seed. Solubility of GaN in supercritical ammonia was studied in a temperature range from 400°C to 600°C and a pressure of about 170 MPa (25,000 psi). Sodium amide and sodium iodide were added to the ammonia as mineralizers. The GaN solubility and its dependence on temperature, pressure, and sodium amide and sodium iodide concentrations was measured. Based on this result, we confirmed a growth system so that the nutrient was placed in the low-temperature zone and the seed crystals were placed in a high-temperature zone. Metallic gallium was used as a nutrient and GaN nucleation was performed in a high-pressure horizontal bulk reactor and laser lift-off was performed as seeds. The thickness of the seeds increased about 8.8 microns after three days of growth. The Ga face gained 5.0 microns and the N face gained 3.8 microns. Both sides of the seed showed band-edge emission in cathodoluminescence measurements. The Ga face also showed luminescence from impurity levels and so-called "yellow luminescence", whereas the N face was free of mid-gap luminescence. The peak position of the band-edge emission showed blueshift for N face. The Ga face was covered with pits and facets, whereas the N face was featureless. The surface roughness measured by AFM was 0.5 nm for smooth regions of the Ga face and 2.06 nm for the N face.

4:30 PM E2.9
Metallocrystal Chemical Vapor Deposition of Non-polar III-Nitride Films over A-plane SiC Substrates. James Li, Zheng Gong, Changhai Chen, Adhikaran Vinod, Michael Gascoy, Edmunds Kuo, Maxim Shatalov, Ying Gao, Zehong Zhang, Arul Arjuman, T.S. Sudarshan, Jinwei Yang and M. Asif Khan; Department of Electrical Engineering, University of South Carolina, Columbia, South Carolina.

Wurtzite III-nitride films grown on non-polar orientations such as (11-20) or (1-100) are very attractive for light emitting devices since the multiple quantum well (MQW) heterostructures over A-plane 4H-SiC. A-plane SiC is more closely lattice-matched to the A-plane GaN than R-plane sapphire. Consequently, better structural quality A-plane nitride films over A-plane SiC substrates are expected. By migration enhanced metalorganic chemical vapor deposition (MEMOCVD), an atomically smooth (11-20) AIN layer with RMS roughness of 0.3 nm was obtained. From the results of XRD, the structural defects in the AIN layer on SiC substrates are strongly reduced compared to those grown on R-plane sapphire. Also by selective area growth procedure we achieved high structural and optical quality A-plane GaN films on 4H-SiC with RMS roughness of 0.05 nm. Therefore, non-polar III-nitride films and heterostructures on SiC substrates are promising building blocks for realizing high performance polarization-free devices.

4:45 PM E2.10
Hydrogen Interactions with the Nitrogen Vacancy in Wurtzite GaN. Alan F. Wright, Sandia National Laboratories, Albuquerque, New Mexico.

Density-functional theory and the generalized-gradient approximation for exchange and correlation were used to identify local-energy-minimum configurations of H near a N vacancy in wurtzite GaN and to compute the formation energies of these configurations as a function of charge state. H sites both inside and outside the vacancy were considered. The lowest energy vacancy-H state in p-type GaN is one wherein H is located near the center of the vacancy. The charge state of this vacancy-H complex is 2 and the binding energy is 1.1 eV relative to the isolated vacancy and H in the 1 charge state and including contributions due to H zero-point vibrations. Paths for H jumps from this configuration to sites at the boundary of the vacancy were also identified. The energy barriers along these paths are sufficiently low that the vacancy-H complex is expected to form during thermal anneals used to activate Mg-doped GaN grown via metal-organic chemical vapor deposition. H compositions were also examined. Local-energy minimum configurations of H near an Mg-vacancy complex in wurtzite GaN and paths for H jumps between sites inside and outside the vacancy will be presented. These results were used to identify the effects of the Office of Basic Energy Sciences, United States Department of Energy. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy National Nuclear Security Administration under Contract DE-AC04-94AL85000.


AIN–SiC alloys, with outstanding physical and electronic properties, are excellent for high power and high frequency electronic device material but also a high power and high frequency electronic device material. For an electronic device material, excess carrier recombinations in the material is the important characteristic and surface conditions of GaN are known to have influence on excess carrier recombinations. In this study, we have measured excess carrier lifetimes in GaN with various doping concentrations and surface conditions by the microwave photoconductivity decay method in order to know how excess carriers recombine in GaN. GaN samples were grown by metalorganic chemical vapor deposition (MOCVD) on Si-face substrates. In the growth, three kinds of doping conditions, Si doped, unintentionally doped and Mg doped, were adopted, and corresponding conductivity types were n-type, high resistive n-type and p-type, respectively. Some pieces of the samples were etched by inductively coupled plasma (ICP) etching and reactive ion etching (RIE) in order to change surface conditions. The microwave photoconductivity decay (μ-PCD) measurements, in which 4th
The as-grown undoped and 10 GHz microwave were employed as excitation light and probe microwave, respectively, were performed using samples. In order to confirm surface-related luminescence, the Auger electron spectroscopy (AES) was also performed to the as-grown and the etched samples. In the decay curve, fast and slow components were observed for all the samples. The time constants of the slow component above 100 ns are determined using fast and p-type GaN show relatively short 1/e lifetime of around 0.1 μs, which corresponds to time constant of the fast component. On the other hand, for n-type samples, the apparent 1/e lifetime values are much larger; in the range of 10-300 μs, depending on relative amount of the slow component. This slow decay will be due to hole traps with a very small electron capture cross section. Since the slow component is more significant in the measurements with excitation from n-GaN/sapphire interface sides. Thus, we think that traps at interface between sapphire and n-GaN are also one of the origins of this phenomenon. The ICP and RIE etching were performed to a thickness of 0.3 μm for n-type GaN, and the photoluminescence decay curve was almost unchanged by the etching. From the AES measurements, the surfaces of the etched samples became strongly Ga-rich. Thus, the surface defect density does not affect excess carrier decay behavior. This may be because the recombination process in n-type GaN is not mainly controlled by the surface defects.

E3.4 Thermal Stability of Boride-based Ohmic and Schottky Contacts on GaN, Roli, Khanna1, C. Jayant, Paul Kraschenko1, F. Ben1, G. C. Oehme1, and Stephen Pearson1, 1MSE, University of Florida, Gainesville, Florida; 2Electrical Engineering, National Central University, Chung-Li, Taiwan; 3Chemical Engineering, University of Florida, Gainesville, Florida; 4Physics, University of Florida, Gainesville, Florida.

Some applications for AlGaN/GaN power amplifiers need extended reliability of the Ohmic and gate metallization at elevated temperatures. There is existing evidence that standard Ti/AI/Pt/Au Ohmic contacts will not have adequate thermal stability. We have investigated chromium boride, tungsten boride and titanium boride contacts deposited by rf sputtering for use on HEMT structures. These materials have high thermal conductivities, in the range of 26-80 Watts per meter per degree Kelvin and electrical resistivities in the range of 1-4 micro Ohm per centimeter. We have found that the self-deposited contacts are always rectifying with poor ideality factors due to the presence of spatter damage but that the contact factors improve with annealing. We present detailed electrical and chemical data showing the transition to Ohmic behavior after high temperature anneals and compare the electrical performance with existing contact metallurgy. There is a clear trade-off between contact resistance and thermal stability.

E3.5 Fabrication and Characterization of GaN Nanopillar Arrays, Yudong Wang1, Tripathy Sudhiranjan2, Soo Jin Chua1,2, and Clifton G Fonstad1,3,1Singapore-MIT Alliance, E4-04-10, 4 Engineering Drive 3, Singapore 117576, Singapore; 2Institute of Materials Research and Engineering, Singapore 117602, Singapore; 3Dept of Electrical and Computer Science, Massachusetts Institute of Technology, Cambridge, Massachusetts, USA 02139, Boston, Massachusetts.

Various nanofabrication technologies are currently under investigation to realize fine patterning of III-Nitrides. Dry and wet etching techniques have been explored in the past for the fabrication of GaN-based devices. However, due to etch-induced damage, it is still a major challenge to achieve high-quality GaN-based nanosheets with high aspect ratio. In this study, GaN nanopillars were fabricated by inductively coupled plasma etching (ICP) using anodic aluminum oxide (AAO) as a mask. High-spatial resolution optical techniques were employed to characterize these pillar arrays. The average diameter and length of these pillars are about 60-70 nm and 290-350 nm, respectively. Room temperature micro-photoluminescence spectra show a red shift compared with the spectrum recorded from the as-grown GaN, indicating stress relaxation in these nanopillars. The evidence of good crystalline quality is also confirmed by micro-Raman measurements where red shift of the E2(2O) mode from GaN nanopillars is 5 cm-1 compared to the as-grown GaN. In addition, due to geometrical shape of the nanopillars, break down of polarization selection rules gave rise to quasi-polar modes in the Raman spectrum.

E3.6 The composition dependence of the optical properties of InN-rich InGaN grown by MBE. Robert W. Martin1, Sergi Hernandez2, Paul R. Edwards1, Ke Wang2, Isabel Fernandez-Torrente1, Masahito Kurouchi3, Yasuhi Naniishi2 and Kevin P. O’Donnell3,1Physics Department, Strathclyde University, Glasgow, United Kingdom; 2Laboratory of Photomaterials, Ritsumeikan University, Shiga 529-8577, Japan.

Direct correlation of the composition and optical energies of relaxed InGaN-GaN has been the main concern for the last decade, driven forward by an increasing range of important applications covering the full spectral range from UV to NIR. A large body of data covers relatively InN-rich (x < 0.4) samples grown by MBE and Reactive Vapour Phase Epitaxy (MOVPE) [1]. However, there are increasing numbers of reports concerning InN and In-rich InGaN grown by Molecular Beam Epitaxy (MBE) [2,3]. Here we concentrate attention on a wide-ranging set of MBE-grown In-rich layers (0.58 < x < 0.97) in order to make comparison with sets of MOVPE and MBE InGaN epilayers with In fractions up to 0.4 measured using identical techniques. We have employed electron probe microanalysis (EPMA) for the accurate measurement of the In fraction and correlated the results with photoluminescence (PL), cathodoluminescence (CL) and optical absorption spectra. The CL, measured simultaneously with the EPMA, interrogates near-identical sample volumes. The other techniques have a much larger footprint. The results show luminescence peak energies covering the range from 1.3 to 0.8 eV for 0.58 < x < 0.97 and shed important light on the composition dependence of the optical properties of InGaN along with differences between samples produced by MOVPE and MBE. The comparison illustrates possible dangers in combining data from samples grown by the two different methods. 1. K.P. O’Donnell et al., J.Phys. C 13 697 (2001) 2. J. Wu et al., Appl. Phys. Lett. 80 4741(2002) 3. V.V. Davydov et al., phys. stat. sol. (b) 230, R4 (2002)

E3.7 Unusual properties of the red and green luminescence bands in InGaN-GaN, Michael A. Reschikov1,2 and Hadis Morkoc'.,2

The yellow luminescence (YL) band dominates the visible part of the photoluminescence (PL) spectrum in most of the GaN samples grown by molecular beam epitaxy (MBE). However, with increasing III/V ratio the relative contribution of the YL band decreases, the layers become more highly resistive, and a non-exponential decay of the lower energy bands, namely the red one (RL) peaking at 1.8—1.9 eV and a green one (GL) at 2.37 eV, dominate the low-temperature PL spectrum [1]. We observed the RL and GL bands in about 50 GaN samples grown by MBE on sapphire under GaN-rich conditions. The transient behavior of the RL and GL bands after pulsed excitation of PL are, however, very interesting and deserve particular attention. Both the RL and GL bands decay exponentially, whereas a nonexponential decay due to donor-acceptor-pair recombination is typical for a majority of radiative acceptors in compensated GaN at low temperatures. Surprisingly, the characteristic lifetime of the RL band decreases by at least two orders of magnitude from 110 to 3 ns as the temperature increases from 15 to 100 K, while its integrated intensity after each pulse remains nearly unchanged in this temperature range due to an increase in the peak intensity in the time-resolved PL curve. The lifetime of the GL band remained unchanged in this temperature range. The unusual behavior of the RL band may provide a clue in attempts to explain the origin of the defect(s) responsible. Tentatively, we assign the RL and GL bands to internal transitions at some point defects caused by excess Ga [1] M.A. Reschikov, R.J. Molnar, and H. Morkoc, Mat. Res. Soc. Symp. Proc. 680, E5.6 (2001).

E3.8 Blue-violet Emission from N+-Implanted ZnO:Ga Films Grown by Chemical Vapor Deposition. Yahtya Ibragimovich Alivov1, Michael A. Reschikov1, Seydi Dogan1, David Look1, Vladimir Zinenko1, Yurii Agafonov1, Badavi M. Ataev1, Valery Mamedov1, and Hadis Morkoc';1Electrical Engineering, VCU, Richmond, Virginia; 2VCU, Richmond, Virginia; 3Semiconductor Research Center, Wright State University, Dayton, Ohio; 4Institute of Microelectronics Technology, Moscow, Russian Federation; 5Institute of Physics, Dagestan Scientific Centre of RAS, Makhachkala, Russian Federation.

Codoping of ZnO with nitrogen and III group metals (Ga, In, Al) is considered to be an effective means of achieving p-type conductivity. In this paper, we implant ZnO:Ga films by N+-ion implantation followed by Chemical Vapor Deposition using an ion energy of 180 keV and ion doses in the range of 1013 to 5x1013 cm-2. The reactivity of the ZnO:Ga films increased with the implanted N+ ion dose. We studied photoluminescence (PL) and cathodoluminescence in the N+-implanted ZnO:Ga films as a function of temperature and excitation intensity. At low temperatures, new intense blue-violet band with a maximum at 3.1 eV and full width at half maximum of about 0.15 eV appeared in the PL spectrum. The intensity of this
band increases and shifts to lower photon energies by about 30 meV after annealing for one hour at 300°C, in contrast to the typical behavior of other reported PL. The PL-induced defects disappear after annealing. A correlation between the intensity of this emission and the ion dose has been observed. Possible mechanisms of the radiative recombination and origin of the defects involved will be discussed.

E3.9 Spatially Resolved Electrical Defect Spectroscopy of Structural Defects in GaN: Andreas Kracht, Hartmut Witz, Armin Dadgar, Juergen Christen and Alois Krolik. Institute of Experimental Physics, Otto-von-Guericke-University of Magdeburg, Magdeburg, Germany.

In the field of electrical defect characterization with conventional techniques like deep level transient (DLTS) or admittance spectroscopy (AS), there still exists one major challenge to solve up to now: to assign the spectral data to specific individual defects or, vice versa, to obtain information on the properties of a distinct local defect. This problem arises from the integral nature of most of these techniques which detect only the sum of all defect related signals in a macroscopic sample region with typically millimeter extension. Here, we present first results of spatially resolved electrical defect spectroscopy at GaN layers which enables the direct local characterization of distinct structural defect species. The samples for our investigations are differently doped GaN layers grown by metal organic vapor phase epitaxy on c-oriented sapphire substrate. The GaN layers were grown by metal organic vapor phase epitaxy (MOVPE) using a Freestanding GaN Substrate with low dislocation density. In this paper, GaN based UV Schottky detector on a freestanding GaN substrate decreased drastically compared with that on sapphire substrate. UV detectors are one of the most attractive devices in the group III-nitride semiconductors. They are used as the flame sensor or the future photolithography system in which the UV interference is filtered through the glass. Therefore, back-mirror AIGaN with high AlN mole fraction is necessary for optical coupling to cover ultraviolet (UV) region because of their direct band gap energy from 3.4 eV to 0.2 eV. For deep UV LEDS and LDs, thick AIGaN with high AlN mole fraction is necessary for optical confinement and transparency. However, it is very difficult to grow thick AIGaN with high AlN mole fraction on GaN because of the AlGaN cracks under the large-in-plane tensile stress. To solve this problem, we have used epilaxial AlN on sapphire as a substrate for the growth of AIGaN with AlN mole fraction of 0.2 < x < 0.8. However, threading dislocation density of the AIGaN is over 10⁶cm⁻². In this study, we have proposed the new approach of fabricating low dislocation density and high AlN mole fraction layer by using a rugged AlN layer on sapphire (0001). No crack is observed in the AlN GaN substrate grown on the rugged AlN template. Cathodoluminescence image of wavelength distribution of AIGaN shows the area of laterally growth and vertically growth, where longer wavelength luminescence was observed in the laterally growth area, while shorter wavelength luminescence was observed in the vertically growth area. This indicates that Al content of vertically growth area is higher than that of laterally growth area. The threading dislocation density in AlN GaN substrate is 8.8x10⁶cm⁻², which is two orders of magnitude less than that of AIGaN on flat sapphire template.

E3.12 Fabrication and Characterization of UV Schottky Detectors by using a Freestanding GaN Substrate. Yasuhiro Shibata1, Atsushi Motogaito1, Hideo Miyake1, Kazumasa Hiramatsu1, Youshiro Oohuchi2, Hiroaki Okagawa2, Kazuyuki Tadatomo2, Tatsushi Nomura3, Yutaka Hamamura3 and Kazutoshi Fukui4; 1Electrical and Electronic Engineering, Mie University, Tsu, Japan; 2Photonics Laboratory, Mitsubishi Cable Industries Ltd., Itami, Japan; 3Core Technology Center, Nikon Corporation, Sagamihara, Japan; 4Research Center for Far-Infrared Region, Fuku University, Fuku, Japan.

We report that GaN substrate is more effective than sapphire substrate for detector. It is because that the dark current density of GaN substrate decreased drastically compared with that on sapphire substrate. UV detectors are one of the most attractive devices in the group III-nitride semiconductors. They are used as the flame sensor or the future photolithography system in which the UV interference is filtered through the glass. Therefore, back-mirror AIGaN with high AlN mole fraction is necessary for optical coupling to cover ultraviolet (UV) region because of their direct band gap energy from 3.4 eV to 0.2 eV. For deep UV LEDS and LDs, thick AIGaN with high AlN mole fraction is necessary for optical confinement and transparency. However, it is very difficult to grow thick AIGaN with high AlN mole fraction on GaN because of the AlGaN cracks under the large-in-plane tensile stress. To solve this problem, we have used epilaxial AlN on sapphire as a substrate for the growth of AIGaN with AlN mole fraction of 0.2 < x < 0.8. However, threading dislocation density of the AIGaN is over 10⁶cm⁻². In this study, we have proposed the new approach of fabricating low dislocation density and high AlN mole fraction layer by using a rugged AlN layer on sapphire (0001). No crack is observed in the AlN GaN substrate grown on the rugged AlN template. Cathodoluminescence image of wavelength distribution of AIGaN shows the area of laterally growth and vertically growth, where longer wavelength luminescence was observed in the laterally growth area, while shorter wavelength luminescence was observed in the vertically growth area. This indicates that Al content of vertically growth area is higher than that of laterally growth area. The threading dislocation density in AlN GaN substrate is 8.8x10⁶cm⁻², which is two orders of magnitude less than that of AIGaN on flat sapphire template.
E3.13 Strain-Induced Effects on the Resonant Tunneling of Holes in Zinc-Blende InGaX:Analytical Theory (B.Radhakrishnan, J.L. Rees, Department of Materials Science and Engineering, Michigan State University, Michigan) and Experimental Results (T. Chiang, D. C. Reynolds, Department of Electrical and Computer Engineering, Wayne State University, Detroit, Michigan). The authors report on the investigation of the strain-induced effects on the resonant tunneling of holes in zinc-blende InGaX, which is a new material system for high performance electronic devices. The theoretical analysis is based on the perturbation theory and the results show a strong dependence of the tunneling probability on the strain. The experimental results are obtained from a novel high-resolution transmission electron microscopy (HRTEM) technique, which allows for the direct imaging of the strain field around the defects.

E3.14 Mesh Patterned Reflectors for High Extraction-Efficiency GaN-Based Light-Emitting Diodes (Hyunsoo Kim, Jaehee Cho, K. Kappers and C. J. Humphreys; Materials Science and Metallurgy, Cambridge University, UK, Cambridge, United Kingdom). The authors present a novel approach to improve the extraction efficiency of GaN-based light-emitting diodes (LEDs) by incorporating mesh patterned reflectors. The method involves the deposition of a porous metal reflector layer, which is designed to selectively reflect light in a particular direction, thereby increasing the extraction efficiency of the LED. The results show a significant improvement in the extraction efficiency compared to conventional methods.

E3.15 Investigation of Pit Formation Induced by the Desorption of InGaX-xN Layer Grown by Metal-Organic Vapour Deposition (Houyong Park, Hoon Park, Jinseok Lee, Wonseok Lee, Ohlyum Nam and Yongjo Park; Photonics Lab, Samsung Advanced Institute of Technology, Yongin-Si, South Korea). The authors study the pit formation induced by the desorption of InGaX-xN layers grown by metal-organic vapour deposition. They investigate the formation of pits on the surface of the layers and correlate the formation of these pits with the desorption of the InGaX-xN layer. The results show a strong correlation between the desorption of the InGaX-xN layer and the formation of pits on the surface of the layers.

E3.16 Excitation Wavelength Dependent Raman Scattering in Low and Highly Degenerate InN Films (Vaman M. Naik, H. Dai, D. Haddad, R. Niu, J. S. Thakur, Gregory W. Aumer, H. Lu and W. Schlaff; U Michigan-Dearborn, Dearborn, Michigan; 2Department of Physics and Astronomy, Wayne State University, Detroit, Michigan; 3Department of Electrical and Computer Engineering, Wayne State University, Detroit, Michigan; 4Department of Electrical and Computer Engineering, Cornell University, Ithaca, New York). The authors report on the excitation wavelength dependent Raman scattering in low and highly degenerate InN films. They study the Raman scattering spectra of InN films grown by various techniques, including Molecular Beam Epitaxy (MBE) and Plasma Source Molecular Beam Epitaxy (PSMBE), and find that the Raman scattering spectra are strongly dependent on the excitation wavelength.

E3.17 Effects of AlGaN and SIN Interlayers in the MOCVD Epitaxial Growth of GaN on Silicon (Matt Charles, M. J. Kappers and C. J. Humphreys; Materials Science and Metallurgy, Cambridge University, UK, Cambridge, United Kingdom). The authors investigate the effects of AlGaN and SIN interlayers on the epitaxial growth of GaN on silicon. They find that the use of AlGaN and SIN interlayers can significantly improve the structural quality and electrical properties of the GaN films.

E3.18 Effect of V_{Ga-ON}^{2+} threading edge dislocations on electron mobility in epitaxial GaN. (Jeong H. You and H. T. Johnson, Department of Mechanical & Industrial Engineering, University of Illinois at Urbana-Champaign, Urbana, Illinois). The authors study the effect of threading edge dislocations on electron mobility in epitaxial GaN. They find that the presence of threading edge dislocations can significantly reduce the electron mobility in GaN, and propose a new model to understand this effect.
Isoelectric doping of GaN with arsenic (As) has long been suggested as an alternative method for achieving blue light emitting diodes. Using photoluminescence (PL) measurements, several research groups have shown that GaN films doped with small quantities of As exhibit strong blue emission at room temperature. Both theoretical and experimental studies have attributed this blue emission to a recombinati

In this study, the fraction of filled traps and the mobility due to cation disorder. We have also observed a mode between the E2 and A1(LO) modes for moderate compositions and the linewidth decreases at both ends of the composition range, as a consequence of reduced momentum-conservation selection rule. Our results show a one-mode behaviour for both E2 and A1(LO) modes of InGaN. This result agrees with the mode behaviour previously reported in InGaN with low In content [2].

Dilute magnetic semiconductor (DMS) has a wide range of potential applications in spintronic devices. DMS Gal-xMnxAs, in which the exchange interaction is mediated by carrier, is widely studied both theoretically and experimentally. The ferromagnetism in these systems is examined in epitaxial thin films of GaMnxAs/DMS with lower (1.9%) magnetic moment compared to Mn ion as well as disorder. Several groups have studied annealing effects on magnetic and transport properties of GaMnxAs/DMS. However, the ferromagnetism and magnetoresistance effect are not well understood in this system. To better understand these behaviors in this system we study the effect of low temperature annealing on the high field magneto-transport properties of epitaxial thin films of GaMnxAs/DMS with lower (1.9%) magnetic moment. Using photoluminescence measurements reveal that the crystal structure of the homogeneous GaMnxAs film is zinc-blende. The Raman spectra from the films also confirm this phase of GaN. The temperature and magnetic field dependence resistivity, magnetoresistance, and Hall coefficient were measured at high magnetic fields up to 17 Tesla and in a wide range of temperature from 5 K to 300 K at National High Field Magnet Laboratory. Annealing at optimal temperature enhances the conductivity and ferromagnetic transition temperatures. The observed field dependence magnetoresistance is different below and above the ferromagnetic transition temperature. Both annealed and as-grown samples exhibit negative giant magnetoresistance (GMR) effect (MR is more than 90% at H = 17 Tesla and at T = 5 K) below the ferromagnetic transition temperature and GMR effect is large in the non-annealed sample compared to annealed sample. However, above the ferromagnetic transition temperature grown sample exhibits unusual positive MR effect up to magnetic field of 17 Tesla. The positive MR effect decreases as the annealing temperature increases and the sample exhibit negative MR effect with optimal annealing. This anomalous MR behavior is confirmed by the observed MR effect of a small fraction of antiferromagnetic phase in the ferromagnetic matrix. The normal and anomalous contributions to the Hall effect have been extracted from the Hall measurement data. The normal component of the Hall coefficient reveals significant increase in carrier concentration due to annealing. At higher temperature anomalous Hall effect is similar for both the sample, however it is drastically different at low temperatures. These results have been compared with the existing theories.
E3.23

Thick layers of gallium nitride have been deposited on 1 μm thick MOVPE GaN(0001) thin film substrates using a novel iodine vapor phase epitaxy system. The system features three concentric flow zones that separate the reactant gases until they reach the substrate. Nitrogen gas flows through the innermost zone delivering iodine vapor from an external bubbler to the molten Ga (kept at 1000°C) and Ga to the substrate; high-purity ammonia flowed through the outermost zone; a nitrogen flow through the middle zone was used to prevent reaction between the growth species at the Ga nozzle. Final growth surfaces were found to be a function of reactant parameters. High Ga supersaturation resulted in a duplex microstructure containing faceted, oriented crystals overgrowing large spiral hillocks (as large as 1 mm in diameter) on the GaN(0001) surface. This microstructure was combined with sample rotation, produced a flatter microstructure after growth. Suppression of cracks by growing very thick layers was also studied. Details of the unique growth system, the growth conditions studied, an analysis of crack formation and prevention, and the microstructures obtained from selected process parameters will be presented.

E3.24
Influence of Junction Temperature on Chromaticity and Color Rendering Properties of Tri-Chromatic Gaussian White Light Sources Based on Light-Emitting Diodes. Sameer Chajed1, E. F. Schubert1, Thomas Geissmann1, Y. L. Li1, and Yangang Xi2; 1Department of Electrical, Computer, and Systems Engineering, Rensselaer Polytechnic Institute, Troy, New York; 2Department of Physics, Applied Physics, and Astronomy, Rensselaer Polytechnic Institute, Troy, New York.

Tri-chromatic white light sources based on light emitting diodes (LEDs) offer a potential luminous efficacy of radiation exceeding 300 lm/W, color temperatures ranging from 2800 K to 6500 K and excellent color rendering properties with a color rendering indices (CRI) exceeding 85. However, the properties of LEDs are strongly temperature dependent. In particular, the peak emission wavelength, spectral width, and the integrated power depend on junction temperature. Here, a detailed experimental and theoretical analysis of the temperature dependence of the tri-chromatic white light LED source is performed. The analysis provides the chromaticity point, CRI, and luminous efficacy as a function of junction temperature. The color temperature changes significantly from 6500 K to 7800 K as the junction temperature increases from 20°C to 80°C. For the same junction temperature range, the CRI changes drastically from 85 to 42. Furthermore, a decrease in the luminous efficacy of radiation from 319 lm/W to 291 lm/W was observed. This decrease is predominantly caused by the shift in the peak emission wavelength of the red emitter towards longer wavelengths. The chromaticity point of the tri-chromatic white light source changes significantly with junction temperature. To maintain the chromaticity point, tunability of the source is required. A high CRI > 80 can be maintained, if the chromaticity point is conserved by power adjustment. However, without such power adjustment the CRI decreases drastically which can render the source unsuitable for certain applications. With the tunability, the source color can be adjusted to cool white or warm white depending on the ambient and personal preference.

E3.25
P-type Doping of AlGaN Alloys by Plasma-Assisted MBE. Wei Li and Theodore D. Moustakas, ECE, Boston University, Boston, Massachusetts.

P-type doping of GaN has been extensively investigated in the past several years. So far, Mg was proven to be the most effective p-type dopant. Contrary to what has been reported in the literature that GaN doping efficiency increases at low growth temperatures due to the high vapor pressure of the Mg, our group reported recently that the p-doping of GaN with Mg by MBE is very efficient when growth taken place at high temperatures and Ga-rich conditions. (1) We attribute the efficient incorporation of Mg under these conditions to the dissolution of Mg on the metallic Ga on the surface and its incorporation to the GaN lattice from the liquid face. In this paper, we report a systematic study of Mg-doped AlGaN alloys with various AlN mole fractions. The films were grown by RF-plasma MBE in the Ga-polar direction by varying a number of kinetic factors, such as the ratio of III/V fluxes and the substrate temperature. The role of the incorporation of Mg was also investigated. So far, we investigated the p-doping of films with up to 25% AlN mole fraction. We found that these films dope more efficiently at higher temperatures (800°C) under group III rich conditions. This result is consistent with our p-type studies of GaN. We also found that electrical and microscopic morphology of the films depends strongly on the Mg flux. Specifically, we found the resistivity is minimum when the Mg cell temperature is between 350°C to 360°C and it increases at lower and higher Mg cell temperatures. The sample with the lowest resistivity has carrier concentrations between 1x1017 cm-3, corresponding mobilities 3-1cm2/V·s. The films grown under optimal Mg temperatures have smooth surface morphology, while those grown under higher Mg flux show evidence of inverted triangular islands. Correspondingly, the cathodoluminescence spectrum of films grown at low Mg temperatures show a single peak at 315nm, while those grown at high Mg flux show a double peak near the band edge and deep transitions approximately in the middle of the gap.

E3.26
Abstract Withdrawn

E3.27
Characterization of the Carrier Confinement for InGaN/GaN Light Emitting Diode with Multiquantum Barriers. Jen-Cheng Wang, Ray-Ming Lin, Tien-En Nee and Nie-Chuan Chen; Electronic Engineering, Chang Gung University, Kwei-Shan, Tao-Yuan, Taiwan.

Much research has been done on high-brightness nitride-based blue/green laser diodes (LDs) and light-emitting diodes (LEDs) for use in varied applications. In order to suppress the carrier leakage and improve the quantum efficiency, a multiquantum barrier (MQB) structure is a very effective approach to increasing the carrier confinement. In this work, we demonstrate that InGaN/GaN multiquantum well LEDs with MQB exhibit better performance in carrier confinement than the LEDs without MQB. The LED samples were grown by metal organic vapor phase epitaxy (MOVPE). The devices with mesa structures were carried out by standard photolithography process. To determine the MQB characteristics, electroluminescence (EL) spectra have been measured as a function of current between 20 and 300 K at a closed He cryocooler. The EL spectra show the MQW peak is observed around wavelength of 440 nm. When temperature is slightly decreased from 300 K, the luminescent intensities for both of the LEDs with and without MQB efficiently increase and reach the maximum at 240 and 200 K, respectively. With further decrease of temperature down to 20 K, it is found that the sample with MQB exhibits a smaller reduction of intensity, the sample without MQB exhibits larger one. The temperature dependence of the EL intensity can be analyzed by a rate equation model. Based upon the experimental observations, excitation cross section (ex), de-excitation cross section (de), carrier lifetime (τ), radiative recombination lifetime (τrad) and nonradiative recombination lifetime (τnrad) are obtained to corroborate the heterobarrier enhancement effect. The different behaviors for the samples with and without MQB can be described by determining the total cross sections as well as the carrier lifetimes. The extracted σex=2.41×1012 cm2 and σde=2.77×1011 cm2 for the sample with MQBs are larger than those for the one without MQBs at 300 K, while the carrier lifetimes at high temperatures are smaller than those at low temperatures for both samples. The EL intensities and the number of the carriers detrapped from MQWs has diminished by heterobarriers, resulting that carrier confinement in the active regions is improved by introducing MQBs in MQW region. Not only the cross sections, but also the carrier lifetimes depend on the MQW design and therefore be mainly attributed to changes in Boltzmann population. All the detailed calculations are also agreement with the observations. These results should greatly aid in the better design and optimization of heterobarriers in optoelectronic heterostructures.

E3.28
Structural property of Eu doped GaN and its relation with luminescence property. Byungjin Bang1, Junji Sawahata2, Takahiro Maruyama1,2, Shigeya Narisaka1,2 and Katsuhiko Akinoto1; 121st Century COE program, Meijo University, Nagoya, Aichi, Japan; 2Department of materials science and engineering, Meijo University, Nagoya, Aichi, Japan; 3Institute of applied physics, University of Tsukuba, Tsukuba, Ibaraki, Japan.

Rare-earth (RE) doped GaN can be regarded as great potential materials in application for optical devices since they show sharp and intense luminescence, which is relatively hard to get in InGaN active layer. We have reported MBE growth of Eu-doped GaN and almost-temperature independent red luminescence observed at 622nm originating from intra 4f-4f transition of Eu2+ ion. The red luminescence was analyzed to be generated through trap-level-related energy transfer from host GaN, and the internal emission efficiency to be approximately 18% at room temperature when Eu concentration is about 2 at %. Those above results revealed that Eu doped GaN is of potential material for an active layer for carrier injection type of LED. In this study, the concentration dependency on optical and structural properties were
studied based on photoluminescence (PL), and X-ray diffraction, extended X-ray absorption fine structure (EXAFS) measurements. Eu-doped GaN epilayers were grown on (0001) substrates by gas-source molecular beam epitaxy (GSMBE) using uncracked NH3 gas with 6% purity as nitrogen source. Metallic Ga with 6% purity and Eu with 3N purity were evaporated from conventional Knudsen effusion cells. MOVPE grown GaN at temperatures of 900°C and Eu doping concentrations were controlled by varying Eu cell temperatures from 300 to 500°C. Eu concentration in GaN was estimated by Rutherford back scattering (RBS) spectrometry. From the PL decay emission at 350 nm, well-developed GaN-Eu2X systems were observed for all Eu doped samples, and those peaks can be assigned as intraatomic 3D2-3F2 transition of Eu3+ ion. Host luminescence starts to be suppressed by Eu doping and completely quenched on Eu 3 at. % (Eu cell temperature is 460°C) doped sample. PL intensity at 622 nm versus various Eu concentrations were studied. The intensity showed linear increase up to the Eu concentration of 3 at. %, and abrupt quenching was initiated when Eu concentration exceeded 3 at. %. From x-ray diffraction patterns obtained by the theta-2theta method, the drastic intensity decrease and broadening of full with at half maximum (FWHM) was observed, no extra peak was observed up to the Eu concentration up to 3 at. %. However, an extra diffraction peak which suggests the existence of secondary phase began to appear with the Eu concentration more than 3 at. %. We consider that those secondary phase formation has close relation with decrease of luminescence intensity. From the result of EXAFS analysis, phase separation between GaN and EuN was analyzed in 15 at. % Eu doped sample and the EuN formation may be responsible to the luminescence quenching.

E3.20
Abstract Withdrawn

E3.30
Extended X-Ray Absorption Fine Structure Studies of InGaN Epilayers. Vintscheslav Katchalov1,2, K. P. O'Donnell1, S. Hernandez1, R. W. Martin1, J. F. W. Mossmann2, Y. Nansh3 and M. Kuroschi2; 1Department of Physics, Strathclyde University, Glasgow, Scotland, United Kingdom; 2Synchrotron Radiation Laboratory, Wattansong, United Kingdom; 3Department of Photonics, School of Science and Engineering, Ritsumeikan University, Shiga, Japan.

InGaN is a remarkable semiconductor alloy offering highly efficient emission and possibility to cover the entire visible spectral region by changing the In content [1]. However, the origin of the InGaN luminescence is poorly understood. It is suggested that high efficiency emission and possibility to cover the entire visible spectral region is due to the formation of transition metal clusters [2]. In the case of formation of metal clusters in InGaN epilayers the average local structure of In should be different from that of random alloy. A powerful tool to obtain information about the local structure of a particular element is Extended X-ray Absorption Fine Structure (EXAFS) [3]. InGaN epilayers grown by Metal-Organic Vapour Phase Epitaxy (MOVPE) and by Metal-Organic Molecular Beam Epitaxy (MObE) with InN fraction ranging from 20% to 90% were studied by means of EXAFS. Difference in the local structure of In was found for MBE and MOVPE grown samples with the same In content. For MOVPE grown samples the In-In and In-Ga chemical ordering is found to be of long-range order. For MBE grown samples EXAFS on In K-edge shows that In-In and In-Ga distances for MBE grown samples obey Vegard's law which is expected for a random alloy. However, for MOVPE grown samples significant deviations from Vegard's law were observed suggesting that in this case a substantial number of In atoms are found in In-rich InGaN clusters. [1] Edited by Bernard Gil, Low-dimensional Nitride Semiconductors, 1st ed. (Oxford University Press, 2002); [2] S. Chichibu, T. Asehata, T. Sota, and S. Namamura, Appl. Phys. Lett. 69, 4188 (1996); [3] http://srs.dl.ac.uk/XRS/index.html

E3.31
X-ray Excited Optical Luminescence studies of InGaN and rare-earth doped GaN epilayers. Vintscheslav Katchalov1,2, K. P. O’Donnell1, S. Hernandez1, J. F. W. Mossmann3 and R. J. Pootlon1; 1Department of Physics, Strathclyde University, Glasgow, Scotland, United Kingdom; 2Synchrotron Radiation Laboratory, Wattansong, United Kingdom; 3Department of Photonics, School of Science and Engineering, Ritsumeikan University, Shiga, Japan.

Conventional X-ray Absorption Fine Structure (XAFS) analysis is a powerful tool to obtain information about the local structure of a solid target by their characteristic X-ray absorption [1]. The main advantages of XAFS as a structural tool are: it is element-specific, so can provide information on the local structure of an element which is present in trace concentrations; and it is completely non-destructive. However, XAFS can provide information only about lattice location of target atoms in d\textit{tmatrixguide}s. Optical luminescence may also be emitted after excitation of core-levels by X-rays [2]. Since the structural environment of recombination centre determines its fluorescence, using X-ray Excited Optical Luminescence (XEOL) for the collection of XAFS data may provide site specific information about optically non-defects or impurities in semiconductors, offering an enormous advantage over other structural techniques. Optically detected XAFS studies of InGaN and rare-earth doped GaN samples were attempted at the Daresbury synchrotron radiation source. It was found that XEOL of GaN:RE was dominated by yellow emission of GaN. Clear Ga N K-edge XAFS oscillations were observed when XEOL was detected at 570 nm. From analysis of XEOL detected XAFS data it has been found that yellow emission of GaN might be associated with certain defects intrinsic to GaN [1]. http://srs.dl.ac.uk/XRS/index.html [2] A. Bianconi, D. Jackson, and K. Monahan, Phys. Rev. B 17, p 2021 (1978).

E3.32
Growth and Characterization of InGaN/GaN LEDs on Corrugated Interface Substrate Using MOVCD. Sungwoo Kim1, Jeong Taek Oh1, Kyu Han Lee2, Dong Juon Kim1, Je Won Kim1, Yong Chun Kim1 and Jeong Wook Lee2; 1Semiconductor Device R&D Group, Samsung Electro-Mechanics, Suwon, Gyeonggi-Do, South Korea; 2Photonics Lab, Samsung Advanced Institute of Technology, Suwon, Gyeonggi-Do, South Korea.

In developing solid-state lighting based on light emitting diodes (LEDs), the light extraction efficiency of LED chip is the important issue. In order to increase the light extraction efficiency, several methods were investigated recently, which was micro-roughening on the surface of LED; transferring LED epitaxy from mirror coated Si to GaAs wafer; patterning the substrate surface to suppress the total internal reflection. In this study, we investigated the influence of GaN on corrugated interface substrate and characterized the structural and optical properties using atomic force microscope, photoluminescence, high-resolution x-ray, and transmission electron microscope. After fabrication of flip chip LED, the optical power of corrugated interface substrate was compared with a conventional substrate and the effect of pattern density was analyzed. We made the hemispheric pattern using inductively coupled plasma etching method and the interface of hemispheric region showed the transition layer with a large lattice constant that was not observed in planar region. Surface morphology of the initial GaN layer had a ruged surface like a corrugated interface substrate. As reactor pressure was reduced, the rugged surface became flattened. The optical power of flip chip LEDs with ruged improved due to the higher extraction efficiency and the higher pattern density showed the higher optical power.

E3.33
Mechanism of Stress Reduction in GaN Epitaxy on Si (111) by Periodic Silicon Delta-Doping. Kyeon Zang1, Soo Jin Chua2,3, Lian Shan Wang2 and Carl V. Thompson1,2,3; 1Singapore-MIT Alliance, Singapore, Singapore; 2Institute of Materials Research & Engineering, Singapore, Singapore; 3Department of Materials Science & Engineering, MIT, Boston, Massachusetts.

The periodic silicon delta-doping technique was employed during metalorganic chemical vapor deposition of epitaxial GaN on AIN buffer layers grown on Si(111). Periodic silicon delta doping during growth of both the AIN and GaN layers led to growth of GaN films with uniform lateral stresses. GaN films grown on AIN buffer layers of various densities, as well as films with improved quality as indicated by x-ray diffraction, micro-Raman spectroscopy, atomic force microscopy, and transmission electron microscopy. The GaN films are composed of grains meeting at low angle boundaries. Periodic silicon delta-doping leads to larger grains in the GaN films, indicating that the coalescence of GaN was delayed in this case. A global energy model suggests that the larger grain size at coalescence observed with delta-doping is responsible for the lower non-thermal component of the intrinsic stress that is observed, as well as the lower dislocation density. Other possible stress relaxation mechanisms induced by delta doping of Si will also be discussed in the paper.

E3.34
Complex Ordering in AlGaN Thin Films. Yi-Yi Wang1, Anirban Bhattacharyya2, Alhmet S. Ozcan1, Theodore D. Moustakas2, Karl F. Ludwig1, Lin Zhu2 and David Smith1; 1Physics Department, Boston University, Boston, Massachusetts; 2Electrical and Computer Engineering, Boston University, Boston, Massachusetts; 3Department of Physics and Astronomy, Arizona State University, Tempe, Arizona.

Several previous studies have reported chemical ordering in AlGaN and InGaN films. Here we report an apparently new complex atomic ordering which depends on the ratio of group III to V atomic concentration. Samples which have equal concentrations of group III and V atoms show ordering of periodicity 4 monolayers. However, nitrogen rich samples show 10 and 16 monolayer ordering simultaneously. Suprathermic peaks associated with these structures
were examined by theta-2theta and off-axis x-ray diffraction and have been confirmed by TEM-SAD analysis as well. Structure factor calculations were used to model the ordered film structure and were compared with observed superlattice intensities. These calculations show that the x-ray diffraction data cannot be explained by only two types of alternating layers. In our calculations, we have also investigated the possible combinations of three alternating layers of different Ga and Al concentrations (Ga-rich, Al-rich and 50/50 Ga/Al). We identified possible arrangements of these three layers that could explain the experimental results. While it has previously been shown [1], [2], [3], [4], and [5] that a mixture of the two main substrates affects the ordering of the films, our studies find no correlation between the nucleation and ordering. [1] E. Iliopoulos, K.F. Ludwig Jr., T.D. Moustakas, Journal of Physics and Chemistry of Solids 64, 1525 (2003). [2] P. Vennema, J. Tesoff, J.A. Floo, E. Chason, D.M. Follstaedt, F. Liu, M.G. Lagally, Nature 397, 678 (1999).

E3-35
Mechanism of Metallorganic MBE Growth of High Quality AIN on Si (111). Julian Gherasoiu, Serguey Nikishin, Gela Gherasoiu, Boris Boronin, Anikulam Chandolu, Mark Holtz and Henryk Temkin; Electrical Engineering, Texas Tech University, Lubbock, Texas.

AIN constitutes the buffer layer of choice for the growth of GaN on all common substrates and its crystalline quality and surface morphology determine many of the properties of the overgrown epitaxial structure. This work systematically investigates the MOMBE growth of high quality AIN on Si (111) using trimethylaluminum and ammonia as sources of aluminum and nitrogen, respectively. Metallorganic MBE represents a hybrid growth technique that offers a combination of growth precision, in-situ monitoring and ease of source management with the promise of high quality material. We demonstrate very efficient growth of AIN with a growth rate in excess of 0.5 μm/h and low ammonia consumption of less than 1% over the entire growth temperature range of 1200 to 1350 °C.

E3-36
Optical characterization of high quality AIN single crystals. Jayantha Senawiratne, Martin Strassburg, Nikolaus Dietz, Ute Haboeck, Axel Hoffmann, Vladimir Noveski, Rafael Dalmau, Raoul Schlesser and Zlatko Sitte; 1Physics & Astronomy, Georgia State University, Atlanta, Georgia; 2Institute of Solid State Physics, Technical University of Berlin, Berlin, Germany; 3Material Science and Engineering, North Carolina State University, Raleigh, North Carolina.

High quality AIN single crystals grown by physical vapor transport and by powder sublimation were investigated optically by means of Raman, photoluminescence (PL), photoluminescence (PC), and absorption spectroscopy. The AIN single crystals were grown under different temperature conditions using precursors, and crucible material in order to analyze and optimize the crystalline structure and quality of AIN bulk material. The absorption edges of the AIN single crystals were investigated by spectroscopic transmission measurements. At room temperature, the absorption edges vary from 4.2 eV to 5.9 eV. Temperature dependent absorption and PL/PC spectroscopy has been applied to obtain additional information about the mid- and near bandgap states. Absorption features between 2.6 eV and 4.5 eV were observed. These characteristics absorption features are correlated to impurities in these crystals as analyzed by Glow discharge mass spectroscopy. The presence of respective impurity states were confirmed by PL investigations either derived from the difference of monocromatic and polychromatic transmission and by band-to-band excitation. The high transparency in the visible and NIR spectral range confirms the absence of transition metal ions. FIR transmission measurements were performed to investigate the intermediate bandgap and multi-phonon related absorption features. The crystallinity of the samples was investigated by Raman and polarization-dependent PL spectroscopy.

E3-37

Enhancement of light extraction in GaN light-emitting diodes (LEDs) employing diffuse reflectors rather than specular ones is presented. The diffuse reflector consists of a SiO2 layer roughened by chemical assisted ion beam etching (CAIBE) and an Ag layer on a GaN surface. This layer is integrated into GaN/AlN LEDs. The GaN/AlN LED structure was grown by metal-organic chemical vapor deposition on p-plane substrate. LED devices were obtained by the CAIBE. Ti/Al/Ni/Ag ohmic contacts to n-GaN are deposited at 500 °C and annealed at 650 °C for 1 min. Ru (5 nm) is deposited on p-GaN and annealed at 500 °C under O2 ambient to form RuO2 acting as ohmic contact to p-type GaN. SiO2 is deposited by e-beam evaporation. In order to roughen the surface of SiO2, various sizes of polymeric nano-spheres are randomly distributed by spin coating and used as etching mask for CAIBE. Then, an array of circular micro-contacts is pattered on roughened SiO2 and etched using HF solution to expose the conducting RuO2 layer. Ag (200 nm) and Au (20 nm) are deposited on the top of the SiO2 with perforated micro-contact holes by electron-beam evaporation. Ray-tracing simulations and theoretical calculations predict higher light-extraction efficiency of diffuse reflectors than that of specular ones by minimizing the trapping of light within a high-index semiconductor. It is experimentally shown that the intensity of diffuse reflector plays a role in the roughness of the reflector surface. It is also shown that the LEDs with diffuse reflectors have higher light-extraction efficiencies than the LEDs with conventional Ag specular reflectors.

E3-38

A detailed modeling of the electronic bandstructure of GaN alloys and GaN/GaN heterostructures typically used for high efficiency light-emitting diodes is of high relevance for future developments. Strong polarization properties of these materials have led to the concept of polarization controlled electronic bandstructure engineering. Here we are exploring opportunities to accurately quantify the net charges present at the individual interfaces. We have employed current-voltage (I-V) and capacitance-voltage (C-V) measurements of GaN/GaN LED-type heterostructures over a wide range of small-signal frequency and modulation amplitudes. Beyond the well-known I-V behavior of a conventional LED our structure shows very distinct steps in the capacitance for voltages that enhance the depletion width. Up to three individual steps can be identified that correspond to alternating ranges of capacitive and resistive impedances. These features can be observed for a very wide range of frequency from 200 Hz up to 15 MHz with a clear transition in behavior around 2 MHz. Our preliminary analysis suggests that the capacitance and charge carrier profile of each individual well can directly be assessed in this way. We will present a study of the dependence of the capacitance on the emission wavelength of the LED-type structure.

E3-39

One of the challenges in III-N research is to achieve high conductivity p-type layers needed for vertical transport devices such as HBTs, LEDs and Laser Diodes. Enhancement of lateral waveguiding and confinement in GaN/AlGaN/GaN heterostructures has been demonstrated recently [1]. Recently, graded n-AlGaN/GaN superlattices have been proposed to enhance the vertical transport [2]. Improved ohmic contact resistance to p-type layers has also been demonstrated by using p-InGaN/GaN superlattices in LEDs [3]. In this paper we propose a band gap engineering technique for optimizing vertical transport in p-type AlGaN/GaN and InGaN/GaN superlattices. This technique leads to a highly conductive p-type layer by reducing the barrier height between the quantum wells and increasing the sheet carrier density. The simulations were performed using a self-consistent 1-D Schrodinger and Poisson solver. The calculated results suggest that the presence of high polarization charges (spontaneous and piezoelectric) together
with the use of modulation and delta doping results in a 6.5 times reduction in the barrier height as compared to uniformly doped classical superlattice structures. The injection increases about 1.5 times for the optimized structures. For the optimized p-type AlGaN/GaN superlattice structure a barrier height of 150 meV and a sheet hole density of 1x10¹³ cm⁻² per period has been achieved. Deposition dopant was successfully used for AlGaN/GaN structures is not applicable for p-type InGaN/GaN superlattices, because the ternary InGaN alloy forms quantum wells. The main approach for reducing the barrier height and increasing the injection (and hence the current density) in p-type superlattices was carried out by introducing acceptor delta doping at the GaN-InGaN interface. This delta doping layer efficiently compensates the high positive polarization charge and reduces the barrier height by around 30%. In this three sheet model, the layer thickness was more than 2 times in the modified structures. A barrier height as low as 215 meV and a sheet hole density per period as high as 1.6x10¹³ cm⁻² has been achieved. The proposed band gap engineering technique holds potential for use in the fabrication of high efficiency, low temperature electronic devices. We reported the effect of mis-orientation angle of c-plane sapphire substrate strongly affects on the growth mechanism of MOCVD grown GaN thin films. In this study, we have observed the morphologies of rather smooth surface of GaN film was obtained on 0.15° mis-oriented substrate and the surface roughness of films was measured by photospectrometry. Crucial point during the deposition was to optimize the O₂/Ar ratio and the working pressure with regard to the film conductivity and stress. The resistivity of 50 nm thick Ru, RuO₂, and Ru-Si-O films was 2x10⁻⁶, 3x10⁻⁶−4 Ωcm, and 1x10⁻³ Ωcm, respectively. Ru films were highly textured, RuO₂ - nanocrystalline while Ru-Si-O - amorphous. RuO₂ films were highly stressed and peeled off. In contrast, Ru and Ru-Si-O layers showed excellent adhesion to nitride substrates. All Ru-based metallization was formed Schottky barriers with n-GaN and InGaN-GaN. Of these, Ru films yielded the lowest contact resistances. RuO₂ films were barrierless, however, Ru-Si-O contact showed significantly lower reverse leakage current and superior thermal stability. Moreover, Ru-Si-O films were found to be optically transparent in the spectral range from 400 to 2200 nm. The transmittance of 50nm thick layer was 88%. The above properties make Ru-Si-O contact a very attractive candidate for gate metallization in GaN-based HEMTs and UV detectors for high speed and high temperature operation. [1] S. M. Gasser, E. Kobawa, M. -A. Nicloet, J. Appl. Phys. 86, (1999) 1974. Work supported by the grant from the State Committee for Scientific Research 3 T11B 008 02."
and of variable thickness (20, 40, 60 and 100 nm) grown on GaN by metalorganic chemical vapor deposition (MOCVD) were studied using temperature dependent photoluminescence (PL) and PL excitation (PLE). At 100 K, highest electron mobility has been obtained for sample with thickness 60 nm due to effective reduction of ionized impurity scattering. In the literature, such 2DEG phenomenon is not discussed for InN quantum wells (PL). In our samples, we have clearly observed such effects from low-temperature PL spectroscopy for AllGaN of epilayer thickness > 40 nm. To investigate the effect of piezoelectric field and AL composition on the growth of AllGaN, we have measured the ratio of integrated intensity of transition for the confined 2DEG and the AllGaN band edge emission. 12DEG/IBE was at low temperature, higher 12DEG/IBE is observed for thinner sample as there is less absorption of emission from 2DEG due to shorter transition distance as compared to thicker sample. With increasing temperature, thermal excitation comes into play leading to faster decline in 12DEG/IBE for thicker sample. At higher temperature, 12DEG/IBE for IBE in the thicker composition caused by composition pulling. The deeper well created by piezoelectric field formed in the thicker AllGaN can be able to prevent carrier leakage by thermal excitation. A band diagram is proposed which is consistent with the experiment.

SESSION E4: Indium Nitride
Chairs: Olivier Briot and William Schiff
Tuesday Morning, November 30, 2004
Back Bay C (Sheraton)

8:30 AM E4.1
Towards Fabrication of Device Quality InN-based III-Nitrides Nano-Heterostructures: Growth and Properties of Thick InN Films, InN-based SQW/MQW Structures, and Quantum Dots by RF-Plasma-Assisted MBE. Takeshi Yoneda, Ryosuke Yoshikawa, Bek Che, Ke Xu, Xiaoqiang Wang, Masayoshi Yoshikawa, Wataru Tershima and Naoki Hashimoto; Department of Electronics and Mechanical Engineering, and InN-project as a CREST program of JST, Chiba University, Chiba, Japan.

Depending on the recent progress on epitaxy technology of InN films, many people now believe that the energy bandgap of InN is about 0.6 – 0.7 eV. In this paper, we have expected to deposit super functional photonic devices in the optical communication wavelengths by using InN-based III-nitrides, such as ultra high speed optical modulators based on InN/InGaN heterostructures. The band gap mismatch between InN and GaN is about 1.1 eV, which makes this material important for extending the application of the nitride semiconductors to the spectral region relevant to fiber optics communication as well as alternative applications, such as photoelectric devices. The most important issue for the growth of this material is the availability of high flux of active nitrogen to prevent decomposition of InN during growth. In this paper, we report the growth and evaluation of the structure and optical properties of InN films by two different deposition methods. In one method, active nitrogen is produced in the form of nitrogen radicals by an RF plasma source. In an alternative method, active nitrogen is produced in the form of clusters containing approximately 2000 nitrogen molecules. These clusters are produced by ablation expansion from high stagnation pressure through a porous nozzle. The InN films deposited in these two methods have been characterized using HRXRD, HRTEM, AES, and RBS.

9:00 AM E4.2
Effects of the Nitridation Process of (0001) Sapphire on Crystallographic Quality of InN Grown by RF-MBE. Daisuke Muto1, Ryotaro Yoneda2, Hironori Nakai2, Tsutomu Araki2 and Yasushi Nanashi1; 1Department of Photonics, Ritsumeikan University, Kusatsu, Shiga, Japan, 2Center for Promotion of the COE Program, Ritsumeikan University, Kusatsu, Shiga, Japan.

InN is expected to be one of the most promising materials for high-frequency electronic devices and long wave length opto-electronic devices. However, it is difficult to obtain high-quality InN crystals. One reason is the lack of suitable substrate materials, which are lattice matched to and thermally compatible with InN. C-plane sapphire substrates are generally used as substrates for epitaxial growth of group III Nitrides. Nitridation process of the sapphire substrate prior to growth improves the crystal quality of InN, due to formation of AlN on the surface of sapphire substrate [1]. However, the relationship between nitridation conditions and InN crystallographic quality has not been systematically investigated in detail. In this paper, we have systematically investigated the effects of nitridation process of the sapphire substrate on InN crystallographic quality by varying the nitridation conditions. InN films were grown by RF-MBE on (0001) sapphire substrates. After the substrate was cleaned by an organic solvent, thermal cleaning was carried out at 800°C. Nitridation proceeded prior to the sapphire substrate growth with time periods of 0.5-3 hours. After the nitridation process, we observed RHEED patterns of each sample to investigate the formation of AlN. InN epilayers were grown at 530°C. In order to obtain a smooth surface, we applied nitridation process for the growth of the InN layer. In our samples, we have clearly observed such effects from low-temperature PL spectroscopy for AllGaN of epilayer thickness > 40 nm. To investigate the effect of piezoelectric field and AL composition on the growth of AllGaN, we have measured the ratio of integrated intensity of transition for the confined 2DEG and the AllGaN band edge emission. 12DEG/IBE was at low temperature, higher 12DEG/IBE is observed for thinner sample as there is less absorption of emission from 2DEG due to shorter transition distance as compared to thicker sample. With increasing temperature, thermal excitation comes into play leading to faster decline in 12DEG/IBE for thicker sample. At higher temperature, 12DEG/IBE for IBE in the thicker composition caused by composition pulling. The deeper well created by piezoelectric field formed in the thicker AllGaN can be able to prevent carrier leakage by thermal excitation. A band diagram is proposed which is consistent with the experiment.

9:15 AM E4.3
Growth of InN Films by Cluster Beam Epitaxy and RF Plasma-Assisted MBE. Takayoshi Chiba, Ke Xu, Xinqiang Wang, Masayoshi Yoshitani, Wataru Terashima and Naoki Hashimoto; Ritsumeikan University, Kusatsu, Shiga, Japan.

Recently, the energy bandgap of InN was found to be about 0.6 – 0.7eV and this indicated that InN-based III-nitrides were applicable to photonic devices in the optical communication wavelengths such as ultra high speed optical modulator. Since the lattice mismatch is about 13%, we can expect to fabricate InN quantum dots on GaN by Stranski-Krastanov (S-K) mode growth.
However, there are only a few reports about the growth and fabrication of InN dots. In this paper we studied the growth and control of InN dots (N-polarity GaN) by using circular beam epitaxy (RF-MBE) and spectroscopic ellipsometry (SE) to systematically investigate the effects of growth temperature, growth time, and V/III beam flux ratio on the diameter, height, and density of InN dots. It is necessary and preferable to grow extremely thin and atomically flat surface by using vicinal sapphire (0001) substrate. We have already clarified that growth temperature and V/III beam flux ratio is an extremely important parameter for the growth of InN quantum dots on nitrogen-polarity GaN. The growth temperature was kept at 600°C and growth rate was set at 0.21 ML/s under both N-rich and In-rich conditions. Growth condition was varied from 4 to 8 seconds (0.84 ML - 8 ML). InN dots growth was monitored, analyzed, and controlled by in-situ reflection high energy electron diffraction (RHEED) as well as spectroscopic ellipsometry (SE). The size, shape, and density of InN dots were characterized by atomic force microscopy (AFM). We first confirmed that S-K mode growth process took place in the initial stage of InN growth by analyzing in-situ RHEED and SE signals. Next, it was found that the critical thickness of InN was affected by V/III beam flux ratio and growth temperature, especially the increase of the critical thickness was observed under In-rich and/or lower growth temperature conditions. And we investigated how the diameter, height, and density of InN dots vary with total supply of InN. Less than 3.5 ML InN deposition, the height and density of InN dots increased with growth time, but the diameter was kept almost unchanged. And InN dots had high uniformity of the height and diameter. More than 3.5 ML InN deposition, because of the coalescence of InN dots, InN dots tended to disappear.

9:45 AM E4.5 Precise Surface Control in RF-MBE of InN Epitaxy by In-situ Spectroscopic Ellipsometry. Masayoshi Yoshitani1,2,3, Song-Bek Che1,2, Yoshhiro Ishitani1,2,3 and Akihiko Yoshikawa4, 1Dept. of Electronics and Mechanical Engineering, Chiba Univ., Chiba, Japan; 2InN-Project as a CREST program of JST, Chiba Univ., Chiba, Japan.

The stoichiometry control in RF-MBE of InN epitaxy was carried out in-situ Spectroscopic Ellipsometry (SE) and RHEED. By measuring dynamic trajectories of the pseudo-dielectric functions, the property of surface during the InN growth can be investigated. The use of in-situ SE monitoring makes it possible to adjust V/III ratio for the stoichiometry condition on InN surface during the growth. Despite of recent improvement of growth technology for InN epitaxy, it is still difficult to get high-quality crystal and atomically flat surface at N-polarity GaN films compared to the case of GaN. This is mainly caused by low decomposition temperature of InN around 600°C and the difficulty of its stoichiometry control. Generally, higher growth temperature is preferable to grow a film with high-quality and flat surface. In this study, however, when the growth temperature was kept at around 600°C or higher, In droplets would appear on the entire surface, because the decomposition temperature of InN is lower than the desorption temperature of In metal. If too much In metal is accumulated on the epilayer surface, the growth of InN layers would be interrupted. In order to grow InN at higher temperatures without In droplet, stoichiometry control is quite important. To prevent the appearance of In droplet, we must grow InN under the N-rich condition. On the other hand, a higher V/III ratio (too N-rich condition) will cause poor surface migration of In atoms, resulting in poor crystal quality and rough surface. Therefore, in the InN epilayer growth, we must precisely control the V/III ratio to the stoichiometry condition. In this study, we used in-situ monitoring of SE and RHEED to investigate and control the surface condition during the growth. SE measurement has a good ability to measure varying of surface states, optical constants, growth rate and amount of roughness. InN samples were grown on GaN layer at 750 - 900°C and were grown in N-polarity. When the growth of InN layers was carried out under the stoichiometry condition, dynamic trajectories of the real and imaginary parts of the pseudo-dielectric functions, ε₁(ω) and ε₂(ω), showed a convolute signal trace and gradually converged on the theoretical analysis. Then we observe a good agreement between the theoretical analysis and experimental results.
InN is a novel semiconductor with low effective electron mass, high mobility and saturation velocity, making it an attractive material for high speed devices. However, the preparation of high quality InN has only recently become possible and many of its fundamental properties have yet to be determined. An important aspect in phonon dynamics in InN, which can affect relaxation times of hot carriers, e.g. a slow longitudinal optical (LO) phonon decay can slow down carrier relaxation, so called hot-phonon effects. We investigate phonon lifetimes over a 77-700 K temperature range in MBE grown InN using Raman spectroscopy. An $\alpha_1$(LO) lifetime of $\approx 2$ ps was measured at 77 K, which is shorter than that reported for GaN, but longer than for defect-free bulk AlN. This lifetime is longer than the current contributions from electron/impurity scattering. Hot phonon effects must therefore be considered in future InN based devices. Phonon lifetimes were found to increase with layer thickness (0.25-1 $\mu$m), reflecting the decreasing defect and impurity levels with increasing layer thickness. The temperature dependence of $\alpha_1$(LO) lifetimes can be explained by a combination of asymmetric two phonon and symmetric three phonon decay channels. The $\alpha_1$(LO) cannot decay symmetrically into two phonons because of a large energy gap in the phonon dispersion, a characteristic of InN. On the other hand, the temperature dependence of $\alpha_2$ phonon lifetimes can be explained by symmetric two phonon and three phonon decay channels. A lifetime of $\approx 2.0$ ps was deduced at 77 K for the $\alpha_2$ phonon. The temperature dependence of phonon frequencies is found to compare well to modelling when anharmonic damping and lattice expansion effects are considered.

### 11:45 AM E4.10
**Unusual Phase Transition in Alloys of GaN, InN and ScN.**

V. Ranjan, S. Bin-Omran, L. Bellaiche, and Ahmad Alsaad;

1Physics Department, University of Arkansas, Fayetteville, Arkansas; 2Department of Materials Science, Jordan University of Science and Technology, P.O. Box 3030, Irbid, Jordan.

We have found that the GaN/ScN and InN/ScN superlattices undergo a pressure-induced structural phase transition (which is a very rare phenomenon) from first-principles calculations. Interestingly, such transition can be continuous (second order), or discontinuous (first order), depending on the superlattice period and the chemical nature of the mixed non-transition-metal cation. The first-principles simulations also reveal how several properties - e.g., total energy, lattice parameters, phonon spectra, piezoelectricity, optical band-gap, born effective charges - vary before, near and after the transition. The calculations also provide a detailed microscopic understanding of these transitions. In particular, the second-order isostructural phase transition is found to be driven by the condensation of a soft transverse optical (TO) mode.

### SESSION E5: Optical Properties

**E5.1** Recombination Dynamics in Low-Dimensional Nitride Systems. Yoichi Kawakami, Akio Kaneta, Kunimichi Omase, Masayoshi Abiko, Ruggero Micheletto, Giichi Marusutki, Yukio Narukawa, and Takashi Mukai;

1Dept. of Electronic Science and Engineering, Kyoto University, Kyoto, Japan; 2Paul-Drude-Institut fur Festkorperelektronik, Berlin, Germany; 3Nitride Semiconductor Research Laboratory, Nichia Corporation, Anan, Tokushima, Japan.

A number of reports have recently been appeared on the spatial mapping of luminescence in In$_{x}$Ga$_{1-x}$N/GaN quantum wells by optical microscope, by cathodoluminescence (CL), or scanning near-field optical microscopy (SNOM). Although spatial resolution of optical microscope is generally a few micrometers, an important advantage of optical excitation by selecting incident laser wavelength in SNOM technique where spatial resolution with nm scale is attainable. PL mapping with SNOM has revealed the dense distribution of island-like structures, the size of which ranges from 20 to 70 nm in a 3 nm-thick In$_{x}$Ga$_{1-x}$N/GaN $(x=0.2)$ single quantum well structure emitting at blue spectral region. Moreover, local diffusion, radiative and nonradiative processes have been identified at room temperature in this structure, by employing multi-mode SNOM where the data of time-resolved photoluminescence are taken in both an illumination-collection and an illumination-mapping mode. It was found that the probe mode can be classified into four different regions whose dominating processes are 1) radiative recombination within a probing aperture, 2) nonradiative recombination within an aperture, 3) diffusion of photogenerated excitons/carriers out of an aperture resulting in localized luminescence and 4) the same diffusion process as 3), but resulting in nonradiative recombination. We believe our experimental technique can be a powerful tool for any nano-photonic materials because of an ability to study quantum wells with nm-scale spatial resolution.

**E5.2** Microscopic Luminescence Properties and Vertical Exciton Transport in InGaN/GaN Light Emitters on Si(111). Till Riemann, Juergen Christen, Karsten Pelzke, Armin Dadgar and Alois Kroetz;

Institute of Experimental Physics, Otto-von-Guericke University, Magdeburg, Germany.

One major advantage of InGaN/GaN light emitting diodes (LEDs) on conductive silicon substrate is the possibility to vertically contact the front side. This directly visualizes the vertical exciton transport from the local active region. One major problem is the cracking of the diode stack at a thickness above one micrometer, which is completely avoided by the multiple insertion of low-temperature AIN, effective reduction of the threading dislocation density is achieved by ultra-thin SiN interlayers. Using cross-polarization CL imaging we can unambiguously identify the light emissions from the individual LED components. In the n-GaN luminescence near 359 nm ($T=6K$) the positions of LT-AIN interlayers are revealed by local mapping of luminescence and $\alpha$) the same diffusion process as the local exciton excitation. Here, no carrier diffusion in $\alpha$-direction is observed, thus giving a direct measure of the spatial CL resolution. In contrast, strong InGaN MQW emission around 470 nm is even detected when the focused exciting e-beam is scanning the underlying n-GaN layer. This directly visualizes the vertical exciton transport from the local excitation position in the InGaN into the InGaN MQW of the active LED region. The vertical exciton diffusion length is assessed by quantitatively evaluating the InGaN MQW intensity profile with respect to the CL excitation position fitted to the 1-dimensional diffusion equation. The impact of diode design, i.e. different interlayer sequences and n-GaN thicknesses, on the vertical exciton transport is discussed. This study is extended to structures where the MQW is embedded between two µm-thick n-GaN layers, giving access to the transport properties underneath and above the MQW.

**E5.3** Microphotoluminescence studies of excitonic and multi-excitonic states of quantum dot-like localization centers in InGaN/GaN structures. E. Scholl, H. Holzer; J. Keganck; S. Einfeldt and Detlef Hommel;

Institute of Solid State Physics, University of Bremen, Bremen, Germany.

There exists a continuous interest in the understanding of the basic optical properties of InGaN-based nanostructures. Especially strong localization centers probably due to fluctuations of the In mole fraction are of fundamental interest because their optical spectra can be characteristics which are typical for quantum dot (QD) structures. To fully utilize their potential for future device
applications the optical properties of single strong localization centers must be studied thoroughly. We report on microphotoluminescence (μ-PL) spectroscopy results that give strong evidence for QD-like centers in the InGaN quantum-well samples and analyze their properties. The samples are grown by metal-organic chemical vapor deposition on (0001) sapphire substrates. At a temperature of 820°C an InGaN layer with a thickness of approximately 4 nm was deposited on a thick GaN buffer layer and capped with another thin GaN layer. The optical investigations are carried out by using a temperature variable μ-PL setup with a spatial resolution of about one micrometer. The samples are excited at 3.82 eV and the temperature dependent sharp emission lines in the region of 2.694 to 2.951 eV are observed on the low-energy shoulder of the InGaN quantum-well photoluminescence. The spectral density of these lines is low enough to investigate the optical properties of the localization centers on unstructured samples. The lines possess a half width of 0.25 meV. With increasing excitation density the energetic positions of these lines remain constant in contrast to the peak of the quantum well photoluminescence which blue-shifts as a result of state filling effects. These observations are a strong indication for the emission lines to originate from complexes possessing a delta-function-like density of states. In coincidence with these findings the emission line spectrum when the excitation density is increased, and additional lines appear at their low-energy side with an energetic distance of about 5 meV, respectively. These lines show a superlinear dependence on the excitation density as is known for multi-exciton states. μ-PL measurements of the single lines in dependence on the temperature are carried out up to 60 K. With increasing temperature the energetic position of the single lines shifts about 2 meV to the red. In contrast to this, the quantum well emission exhibits an even larger red shift. This behavior is attributed to preferential filling of quantum states from shallower localization states in the InGaN quantum well emitting light at the high-energy side of the spectrum. Because this redistribution of carriers in the quantum well is an ensemble effect it cannot be observed for the sharp lines. Moreover, the spectral broadening of the sharp emission lines and the activation energies of the strong localization centers are determined by temperature variable μ-PL measurements.

2:30 PM E5.4 Franz-Keldysh Effects on Ultrafast Carrier Dynamics in an InGaN Thin Film
Chih-Chung Teng¹, Chih-Chung Yang¹, Rung-Jen Ma², Chang-Chi Pan³ and Jen-Inn Chyi²; ¹Graduate Institute of Electro-Optical Engineering, National Taiwan University, Taipei, Taiwan; ²Department of Electrical Engineering, Chung Hua University, Taipei, Taiwan; ³Department of Electrical Engineering, National Central University, Chung-LI, Taiwan.

Because of the large lattice mismatch between GaN and InN, two prominent phenomena InGaN compounds have been widely observed, including indium composition fluctuation (or clustering) in such a compound and strain-induced piezoelectric field near an interface of hetero-structures. The former leads to carrier localization and hence radiative recombination efficiency. The latter results in potential tilt and hence carrier separation in a carrier confined structure. Both phenomena are crucial to photon emission mechanisms in such a compound. For understanding the optical properties of such a material, ultrafast carrier dynamics observed with fs pump-probe experiments has been an effective tool for exploring the photon emission mechanisms. Carrier flow information can help us in understanding the nano-material structures, which will provide us the clues for light emission origins. In this study, we perform fs degenerate pump-probe experiments on an InGaN thin film, in which piezoelectric fields due to composition inhomogeneities and/or heterostructure exist. The InGaN thin film sample was grown on c-plane sapphire with MOCVD. After the 800-nm GaN buffer layer, a 600-nm InGaN thin film with silicon doping of 5 x 1018 cm^-3 in concentration was grown at 800°C. The nominal indium content was estimated to be 20%. We observe quasi-periodical temperature-, pump-power-, and pump-photon-energy-dependent variations of carrier dynamics that are attributed to the Franz-Keldysh effect, transient carrier screening, local band gap renormalization, and band gap shrinkage in increasing temperature. Two-photon absorption and free-carrier absorption can be clearly observed when differential one-photon absorption is small. The calibrated Franz-Keldysh oscillation period of 120 meV is consistent among different measurements, including absorption and free-carrier absorption experiments. From this value, the piezoelectric field in the InGaN film is calibrated to be around 0.22 MV/cm, which is in the reasonable range of the previously reported. It is speculated that this piezoelectric field originates from the large atomic radii mismatch between the formed indium-rich clusters and the surrounding background InGaN compound besides the possible residual hetero-structure-induced strain distribution.

2:45 PM E5.5 Efficient Luminescence from \{11.2\} InGaN/GaN Quantum Wells.
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In light emitting diodes composed of InGaN/GaN QWs, the piezoelectric polarization causes the QCSE and degrades the internal quantum efficiency. Therefore, eliminating the QCSE is important to achieve higher device performances. To find a clue, we calculated the variation of the external quantum efficiency due to the piezoelectric polarizations as a function of the tilt of the c-axis and found that the piezoelectric field is 0 for any In compositions when the tilt is 40 or 90 degrees. The growth on non-polar planes has already been attempted, though it is generally more difficult to grow on non-polar substrates. On the other hand, there is no report on the growth and optical characterization of QWs on tilted planes. In this study, we propose the re-growth technique, where well-established and high-quality c-oriented GaN is used as a seed and demonstrate that tilted \{11.2\} QWs can be fabricated on the growth facet and has a higher luminescence efficiency compared with conventional c-oriented InGaN QWs. The 4-micron-thick GaN template was firstly grown on a (0001) sapphire substrate by MOVPE. Then, a stripe pattern was formed along the [1.00] direction, and so the sidewalls are \{11.0\} planes and the top plane is (0001). The GaN template was deeply etched to the sapphire substrate, which works as a mask. Then, three periods InGaN/GaN MQWs were grown. After the growth a cross section was observed by STEM from the [1.00] direction and it was found that \{11.2\} facets as well as (0001) and \{11.0\} appeared. Furthermore, the STEM observation confirmed the successful fabrication of MQWs on all the growth facets. The In and composition were estimated to be 5.8 nm and 13.5% for (0001), 2.8 nm and 7.5% for \{11.2\}, and 2.2 nm and 2.4% for \{11.0\} MQWs. Using the obtained parameters and taking the electric fields into account, the transition energy of excitons under the presence of the electric fields was calculated. The calculated lifetime for the \{11.2\} MQW is the strongest among the three MQWs, and the internal quantum efficiency of the \{11.2\} MQW was estimated to be about 24% at RT. The radiative recombination lifetime of the \{11.2\} MQW was about 0.38 ns at 13 K, which is shorter than that of conventional c-oriented InGaN QWs emitting at a similar wavelength of about 400 nm. To provide a theoretical support, the spontaneous emission lifetime of excitons under the presence of external fields was calculated. The calculated lifetime for the \{11.2\} MQW agrees well with the experimentally obtained lifetime at low temperature. Namely, the faster lifetime is a clear evidence of the reduction of the electric field in the \{11.2\} MQW, and the better internal quantum efficiency of 40% is a consequence.
domains with different local Mg concentrations are observed by NSOM and SKPM. For GaN:Mg with an average Mg concentration of 4x10^{18} cm^{-3}, the pyramidal structures are observed. The thickness of these pyramids is determined to be 300 nm for the regions away from the large pyramids, but 3 μm for regions on the pyramids. Second phase precipitates are observed at the centers of the pyramids by NSOM, which is related to the formation of Ga droplets at the terminating end of pure screw dislocations.

3:45 PM E5.7
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Carbon doping of GaN is important for generating semi-insulating (SI) buffer layers for high performance AIGaN/GaN heterojunction field effect transistors (HFETs) grown by MBE. However, the specific mechanism(s) responsible for SI behavior involving C-related bandgap states in GaN remain unverified experimentally and must be understood to optimize this important device layer. Moreover, C-related deep states in GaN are under increased scrutiny due to observation of yellow luminescence (YL) in both n-type and SI GaN. This has led to the questioning of a unified picture for the source of the YL band in GaN, as various explanations have been put forward to explain the well-known V_{Ga} defect commonly associated with YL in n-GaN, is not expected to form in significant concentrations for SI GaN. The fact that YL indeed is observed for SI GaNC, but not for SI GaN:Fe, requires understanding of C-related deep states in SI GaNC to achieve a comprehensive picture of YL in GaN. Here, motivated by the need to fully understand the mechanism of achieving SI behavior in GaNC, coupled with the fundamental question of YL behavior in SI GaN material, we present the results of a systematic study of GaNC samples grown by MBE spanning n-type to compensated and fully SI behavior. Due to the expected deep nature of C-related traps in the wide GaN bandgap, defect level optical spectroscopy is extensively used to understand the thermal activation properties, deep trapping and recombination properties of DLTS-type methods to quantify trap positions and concentrations throughout the entire bandgap. A new approach is developed, based on DLOS and lighted C-V defect profiling, that quantifies deep trap energies and concentrations even for SI GaN. Using this methodology, several states are found to depend strongly on C-doping and conductivity, at Ec=1.35, 1.94, 2.54 and 3.28 eV. Comparable with earlier work and theoretical calculations indicate the association of the Ec=1.35 eV state with C interstitials that may be enhanced by dislocations, whereas the Ec=3.28 eV state is related to the Mg acceptor, the only acceptor useful for p-doping of GaN, and is reported for acceptor-doped GaN. The Ec=2.54 eV state is consistent with C-related traps and is related to two deep levels, defect levels 1 and 2, that require further study to determine their origin and nature. The new methodology for trap studies in wide gap SI materials, V_{Ga} and C-related deep states in GaN, provides a new approach to understanding the optical properties of GaN and the origin of YL in GaN.

4:00 PM E5.8
Near-field Optical Spectroscopy of GaN/AlN Quantum Dots. Arup Neogi1, Hadia Moroč1, Brian P. Gorman1, Atsushi Tadano2, Tadashi Kawazoe2, Motoichi Ohtsu5; 1Physics, University of North Texas, Denton, Texas; 2Laboratory of Physics, University of Tokyo, Tokyo, Japan; 3Physics, University of Virginia, Charlottesville, VA; 4Applied Physics, Waseda University, Tokyo, Japan; 5Electrical Engineering, University of Tokyo, Tokyo, Japan.

Quantum dots (QDs) in nitride-based structures are expected to improve characteristics of visible-to-UV optical emitters that are currently developed by employing 2- and 3-dimensional growth processes. Optical properties of QDs are particularly interesting as it determines the internal quantum efficiency (IQE) and analyzed its temperature and excitation power dependence. The maximum room temperature efficiency obtained was more than 10% in case of a GaN/AlN superlattice. While the room temperature efficiency reaches significant values in excess of one percent only at fairly high excitation power density, the full power dependence reveals that radiative free exciton recombination competes with nonradiative recombinations. Compared to GaN-based structures, the nonradiative lifetime at room temperature is much shorter.

4:30 PM E5.10
Oxygen-related Shallow Acceptor in GaN. Bo A. Monemar1, Plamen Paskov1, Filip Tuomisto2, Kimmo Saarinen2, Hiroshi Amano3, and Isamu Akasaki3; 1Dept of Physics and Measurement Technology, Linköping University, Linköping, Sweden; 2Laboratory of Physics, University of Helsinki, Helsinki, Finland; 3Department of Electrical and Electronic Engineering, Meijo University, Nagoya, Japan.

The optical signatures of the shallow acceptors in GaN are still not established. A very commonly occurring and often strong DA pair (DAP) emission in photoluminescence (PL) with a no-phonon peak at 3.27 eV [1,2] is related to a residual acceptor that is so far not identified. In recent years it has been suggested that the DAP emission is related to the Mg acceptor, the only acceptor useful for p-doping of GaN. Mg doping introduces a broad PL band peaking at about 3.1 eV, however, typically consisting with the 3.27 eV DAP [3]. Various other suggestions have been made for the corresponding acceptor,
The PAE and output power are still increasing with Pin at a power density of 5.7 W/mm, indicating with 7 W/mm output power density. At 30 and 45 frequency bands such as K, Ka-, Q-, and V-band, there has been very stable over a large temperature range [7], while the acceptor related suggested acceptors with corresponding doping experiments have been studies on the fresh dislocations induced by the plastic deformation in optical PL data. A model for the identity of the 3.27 eV acceptor will drastically in the deformed specimens by about 1/100 than that of decrease strongly while RB developed relatively, which seems to imply density of non-radiative recombination centers into GaN during the double acceptor is related to the so called yellow luminescence (YL) induced trapping under high Vds and high RF power operation. Thus, in the deformed crystals (a/6)


Deep-Submicron Gate-Recessed and Field-Plated AlGaN/GaN HFETs for mmWave Applications, Jeong Moon1, Shihching Wu2, D. Wong1, I. Milosavljevic4, P. Hoshimoto1, M. Hu1, M. Antcliffe5 and M. Micovic1; 1HRL Laboratories, Malibu, California; 2Boeing Laboratory at Boston University. The parts were processed jointly by Photronix and BU. The AIN substrates were supplied by Solid State Scientific Corporation, Hollis, New Hampshire, 4Air Force Research Laboratory, Bedford, Massachusetts.

A novel GaN device for advanced T/R Modules for X-band radar is a goal of this work. It is a thick gate FET using the submicron recessed and FP GaN/GaN HFETs are fabricated using SiNx masking and Cl2 plasma etching, similar to the process reported in 2002, on the materials grown on semi-insulating (6H) 4H-SiC substrates using RF-assisted MBE. The gate foot dimension ranges from 0.23 um to 0.14 um, with a recess depth of 10 nm. The gate-recessed and FP devices showed Idss of 0.7 A/mm with pinch-off voltage of approximately 2 V. The measured PAE at 20 V, the measured DE and PAE at P1dB was as high as 600 mV/mm, comparable to that of GaAs PHEMTs. Small signal RF measurements showed a unity-gain cut-off frequency (f0) of 100 GHz, and maximum oscillation frequency (fmax) of 100 GHz, respectively, with Lg = 2.5 um. Maximum stable-gain (MSG) scaling up to 1 mm gate periphery was measured. Pulsed IV characteristics were measured using 200 nm sec pulses, exhibiting no sign of knee voltage walkout. Device MW/MMW power performance was measured at 10 GHz and 30 GHz in terms of Vds and Wg up to 1mm. At 10 GHz, output power density of 11 W/mm was obtained with PAE of 50% at Vds = 30 V. PAE was measured as high as 59% with 7 W/mm output power density. At 30 GHz, with Vds = 20 V, the maximum output power density of 9.5 W/mm was obtained with PAE = 62%. RB was as high as 58 % and 54% at a power density of 6.7 W/mm, indicating the highest ka-band performance ever reported from GaN HFETs. Most importantly, the measured performance is superior to that of the current state-of-the-art GaAs PHEMTs. At Vds = 28 V, the output power density at P1dB was as high as 6.9 W/mm was obtained with PAE > 30 %. The PAE and output power are still increasing with Pin at the P1dB point. The output power density and PAE of gate-recessed and FP AlGaN/GaN HFETs are almost twice those of baseline planar AlGaN/GaN HFETs. Detailed comparison will be presented. This work was partially supported by ONR, monitored by Dr. Harry Dickitch.


A GaN-based Schottky barrier diode (SBD) with dual Schottky metal structures was proposed for realizing a low on-voltage. However, there is no report for GaN SBD gate-recessed and FP AlGaN/GaN HFETs were fabricated using SiNx masking and Cl2 plasma etching, similar to the process reported in 2002, on the materials grown on semi-insulating (6H) 4H-SiC substrates using RF-assisted MBE. The gate foot dimension ranges from 0.23 um to 0.14 um, with a recess depth of 10 nm. The gate-recessed and FP devices showed Idss of 0.7 A/mm with pinch-off voltage of approximately 2 V. The measured PAE at 20 V, the measured DE and PAE at P1dB was as high as 600 mV/mm, comparable to that of GaAs PHEMTs. Small signal RF measurements showed a unity-gain cut-off frequency (f0) of 100 GHz, and maximum oscillation frequency (fmax) of 100 GHz, respectively, with Lg = 2.5 um. Maximum stable-gain (MSG) scaling up to 1 mm gate periphery was measured. Pulsed IV characteristics were measured using 200 nm sec pulses, exhibiting no sign of knee voltage walkout. Device MW/MMW power performance was measured at 10 GHz and 30 GHz in terms of Vds and Wg up to 1mm. At 10 GHz, output power density of 11 W/mm was obtained with PAE of 50% at Vds = 30 V. PAE was measured as high as 59% with 7 W/mm output power density. At 30 GHz, with Vds = 20 V, the maximum output power density of 9.5 W/mm was obtained with PAE = 62%. RB was as high as 58 % and 54% at a power density of 6.7 W/mm, indicating the highest ka-band performance ever reported from GaN HFETs. Most importantly, the measured performance is superior to that of the current state-of-the-art GaAs PHEMTs. At Vds = 28 V, the output power density at P1dB was as high as 6.9 W/mm was obtained with PAE > 30 %. The PAE and output power are still increasing with Pin at the P1dB point. The output power density and PAE of gate-recessed and FP AlGaN/GaN HFETs are almost twice those of baseline planar AlGaN/GaN HFETs. Detailed comparison will be presented. This work was partially supported by ONR, monitored by Dr. Harry Dickitch.
with a low on-voltage. We have recently proposed a novel field effect Schottky barrier diode (FESBD) with a dual Schottky structure combined with a GaN based metal organic chemical vapor deposition (MOCVD). This diode, when used as a normally-off operation using GaN based HFETs.

9:30 AM E6.4
ALGa/GaN HFETs and Insulated Gate HFETs DC and RF Stability, Salih Saygi, Alesl Koutmynov, Grigory Simin, Vinod Advanarany, Shiva Rai, Jinwee Yang and M. Asif Khan, Electrical Engineering, University of South Carolina, Columbia, South Carolina.

The comparative study of the DC parameters and RF power stability of nitride-based conventional and Metal-Insulator-Semiconductor (MIS) HFETs was presented. The average time period of the power storage parameters stability is estimated to be as high as 2.5 years at room temperature. The failure analysis demonstrates that for conventional HFETs, the leakage of the gate increases significantly with time under the RF drive close to saturation. The failure is due to the degradation on the device mobility. Several test structures such as transmission, TLM, or MOS capacitors were tested to identify the device degradation mechanisms. The device failure was found to be reduced by the presence of a strong electric field near the drain region of the device.

9:45 AM E6.5

The GaN field effect transistor (FET) can operate under high-power, high-frequency, and high-temperature conditions, which the GaN has excellent figure of merits for these purposes. Especially, the specific on-state resistance (Ron) of the FET is expected to be lower than that of Si based FET. That is, using GaN-based electronic devices, a portable switching device can be achieved. The on/off ratio of the converters can be reduced compared with that of conventional Si devices, resulting in the reduction of cooling system. Since a GaN-based FET is also expected to have a higher switching speed, and a high on-state resistance, a high efficiency of power supply can be realized by using GaN-based FETs. A normally-off FET is necessary for switching devices. However, there are very few reports for normally-off operation using GaN-based HEMTs. The enhancement mode GaN-based HEMTs using an isolated gate structure has been very difficult, since a high quality gate insulator could not be formed in the case of GaN-based FETs. We have demonstrated the normally-off HFETs using a C-doped GaN as a channel layer. A higher temperature over 1273K. However, due to compensating the carrier, maximum current is limited using a C-doped layer. In order to obtain high power operation, we examined the possibility to decrease the AlGaN thickness for normally-off operation. In this paper, we fabricated the normally-off AlGaN/GaN HFET using an accurately controlled thin AlGaN layer on Si substrate. A heterostructure of an undoped AlGaN (5nm) / AlN (1nm) / GaN (500nm) / AlGaN buffer / Si (111) substrate was grown using metal-organic chemical vapor deposition (MOCVD). The thickness of the heterostructure was also precisely controlled to obtain a normally-off operation. After that, the HFET was fabricated. The gate width was 200nm and the gate length was 2um. The distance of source and drain of diode was 2um. Furthermore, we fabricated a normally-off FET using two types of contact layers were not fabricated. The gate bias was 0V, Ids was less than 1µA/mm. The breakdown voltage of the HFETs was over 360V. The maximum current was 9A. The Ron was about 300mΩ. The performance of the normally-off FET was measured under DC and RF conditions.

11:00 AM E6.7
High Performance GaN Field-Effect Transistors Grown by MOVPE with in-situ SiN Surface Passivation, Marius Leuven, Belgium.

Although AlGaN/GaN High Electron Mobility Transistors have demonstrated outstanding power capabilities, trapping effects by surface states remain an important concern. Surface related phenomena are responsible for the steepest roll-off at high drain-source voltage and/or DC to RF dispersion. To minimize the impact of interface states on device performance, passivation of the top AlGaN surface with SiO2 or Si3N4 (PECVD) appears in many cases an effective way of improving device performance. However, ex-situ passivation is a very sensitive step, since it is strongly dependent on several factors which are difficult to control accurately. On the one hand, due to the presence of native oxide, the strain state of the overall heterostructure has a direct impact on the channel properties; this includes the strain due to misfit dislocations. The presence of these defects can be minimized by using a low damage growth technique such as MOVPE. In addition, the use of in-situ surface passivation is an attractive alternative. However, the technical challenges associated with in-situ passivation are significant. In this paper, we present a novel MOVPE growth process for AlGaN/GaN HEMTs with improved in-situ SiN surface passivation. The process is based on a high quality MOVPE growth on sapphire, followed by an in-situ RF plasma treatment. The passivation process is completed by a low temperature annealing step. The impact of this process on the interface quality and device characteristics is investigated using various characterization techniques, including X-ray reflectivity, X-ray diffraction, atomic force microscopy, Hall effect, C-V profiling, and Shubnikov-de Haas measurements. The investigated samples have shown that the combination of high-quality MOVPE growth and in-situ SiN passivation results in excellent device performance. The resulting HEMTs exhibit high on-state current densities and low on-state resistance, making them suitable for high-frequency applications.
Si₃N₄ layer, which changes with growth conditions. On the other hand, reproducibility and homogeneity of the results strongly suffer from a poor control of the AIGaN surface prior to passivation. To increase HEMT performance, to improve reproducibility and homogeneity of the processing as well as of the device characteristics, we propose to passivate the III-N surface of the piezoelectric device in-situ, by depositing Si₃N₄ in the MOVPE reactor, after the deposition of heterostructure growth. AIGaN/GaN HEMT heterostructures have been grown by Low-Pressure MOVPE on sapphire substrates. A thin AlN spacer layer is introduced between AlGaN and GaN layers to improve mobility and electron density. The 2 DEG is disturbed in the top AlGaN layer, a thin Si₃N₄ layer is grown in-situ at high temperature, using SiH₄ and NH₃ as sources. A reference sample without in-situ passivation has also been grown under identical growth conditions. Transistors were prepared on these structures through standard processing, without removing the top Si₃N₄ layer. Transmission Line measurements show a reduction of the ohmic contact resistance and a large improvement of the I-V characteristic under high temperature conditions. Active layers were compared to results obtained with ex-situ Si₃N₄ passivation. The DC and RF characteristics will be analyzed in detail, taking into account surface states as well as strain state modification in the heterostructure (X-Ray reciprocal space map) and its impact on the channel properties. Power measurements will also be reported.

11:15 AM E6.5
High Quality AlGaN/GaN/AlN Based HEMT Structures on Bulk AlIN Single Crystal Substrates for RF Applications.
Qahid Fareed1, Xuhong Hu1, Jianyu Deng1, Remis Gaska2, Michael Shur2, Edmundus Koukists3 and M. Asif Khan2; 1Sensor Electronic Technology Inc., Columbia, South Carolina; 2Dept. of ECE and CIE, Rensselaer Polytechnic Institute, Troy, New York; 3Dept. of Electrical Engineering, University of South Carolina, Columbia, South Carolina.
High electron mobility transistors (HEMTs) have emerged as a promising candidate for microwave (f > 1 GHz) power amplification, with applications ranging from satellite links to wireless communication. All the present HEMTs are fabricated on sapphire or semi-insulating SiC which has a large lattice mismatch leading to high dislocation density in the epilayers. The traps and defects are main reason for the current collapse phenomena in the HEMT devices. Bulk AlIn single crystal are promising and viable substrate for high power, and high temperature electronic devices. The use of a bulk AlIN substrate should allow us to reduce the dislocation density in the epilayers by more than four orders of magnitude down to 10⁵ cm⁻². At the same time bulk AlIN substrates have superior thermal conductivity (3 W/cm-K or higher) compared to sapphire or semi-insulating 4H-SiC (3.9 W/cm-K) which will significantly improve the device performance. In the present paper, we report on the growth of high quality homoepitaxial AlGaN/GaN/AlN HEMT structure over c-plane Al-face with 1-14 degree off axis bulk AlIN single crystal substrates. The homoepitaxial AlIN buffer layers have been grown using conventional metalorganic chemical vapor deposition (MOCVD) and Migration enhanced MOCVD (MEMOCVD). Photoluminescence studies show significant improvement in epilayer quality for MEMOCVD grown layers compared to MOCVD layer with 2-3 orders of magnitude reduction in deep level defects. Atomic force microscopy (AFM) studies on AlGaN/GaN heterostructure show a root mean square roughness less than 8Å. The 2-DEG rocking curve measurements shows full width at half maximum of less than 50 arc sec for homoepitaxial AlGaN epitaxial layer. The AlGaN/GaN structure with Al composition varying from 22-29% in AlGaN barrier layer have been grown. Standard HEMT devices have been fabricated on these high quality epitaxial layers. The DC and RF characteristics have been carried out and show promising results. The development of high-power, high frequency (X-band) transistors on bulk AlIN substrate will be building blocks for a new generation of ultra-high microwave power amplifiers.

11:30 AM E6.6
The mobility and concentration of the two dimensional electron gas (2 DEG) in high electron mobility transistors (HEMTs) based on AlGaN/GaN heterostructures is affected strongly by deep defects and dislocation densities in the AlGaN/GaN layers. A crucial question is the location of the defects and their impact in causing a low 2 DEG mobility. We therefore combine transport measurements and defect spectroscopic (thermal and optical) methods. A series of HEMT structures grown by metal organic vapor phase epitaxy on high resistivity Si-substrates using an iron doped GaN buffer layer was investigated. Two groups of HEMT structures were distinguished: for the first group the 2 DEG mobility is larger than 800 cm²/Vs, whereas for the second group the mobility decreases down to 20 cm²/Vs showing a reduced mobility. To investigate the transport properties as well as the photo-induced recharging effects caused by deep defects, temperature dependent and photo Hall effect measurements were carried out. For this purpose, the samples were measured in a temperature gradient measurement set-up in order to measure characteristic of the traps. The different band edge absorptions of the GaN and the AlGaN layers in the photo-Hall effect enables the localization of deep defects in the HEMT structures. In addition the locations of the individual layers and space charge regions were determined using surface scanning potential spectroscopy. The absorption edges were independently determined using photoreflectance spectroscopy. In optical and thermal admittance spectroscopy and in deep level transient spectroscopy the space charge regions of both, the AlGaN and the GaN layers, were individually investigated by varying the bias voltage at the Schottky contact. In the GaN layer the persistence effect in the photo-Hall decay showed larger time constants for disturbed samples than for samples with a high mobility. This indicates a high concentration of electron traps. Furthermore, a recharging of hole traps inside the GaN layer was observed. Activation energies between 50 meV and 400 meV were obtained from the temperature dependence of the decay time constants. In HEMT structures with a high 2 DEG mobility the electron mobility is affected only by defects in the AlGaN layers whereas defects in the GaN layers showed no influence. In contrast, in disturbed HEMTs the mobility is essentially reduced by electron traps inside the GaN layer. The well known optical and thermal transition energies of these traps are in the range between 100 meV and 600 meV.
Semiconducteurs, Universite Montpellier II - CNRS, Montpellier, France.

There is a major interest in fabricating III-nitride photonic structures for efficient non-linear optical processes such as second-harmonic generation because they offer fairly large non-linear coefficients and high optical densities. However, this has not been possible practically due to the high dispersion and the small birefringence for phase-matching. We have proposed the possibility of obtaining enhanced second-harmonic generation by employing GaN-based photonic crystals. Porous GaN etched into a semiconductor material can produce a photonic band structure, with photonic band gaps that prohibit the propagation of light - and with resonant Bloch modes that confine the light incident on the surface of the photonic crystal. Experimental data and theoretical work have demonstrated that efficient second and third harmonic generation can be realized in one-dimensional and two-dimensional GaAs-based photonic crystal structures. In particular, it has been predicted that photonic crystals should provide giant enhancement as a result of strong confinement and quasi-phase matching (QPM) behaviour. Photonic crystals patterned into III-nitride layers will offer opportunities for enhancing non-linearities and designing novel photonic devices in the near-ultraviolet and visible spectral regions. Recently, we have shown experimentally the enhancement of second-harmonic generation in epitaxial GaN-based photonic crystals. By using calculated and experimental equifrequency surfaces, it is possible to identify the geometrical configurations that will allow quasi-phase matching to be satisfied - and observed experimentally in the available wavelength tuning range of the laser. The second-harmonic field generated has been measured in reflection from the surface of one-dimensional and two-dimensional photonic crystals etched into a GaN layer. A very large second-harmonic enhancement is observed when simultaneously the incident fundamental frequency excites a resonant Bloch mode and the second-harmonic field is generated into a resonant Bloch mode at 2ν. A smaller, but still substantially enhanced, second-harmonic generation level was also observed when the fundamental field was coupled into a resonant Bloch mode, while the second-harmonic field was not. Experimental second-harmonic intensities are successfully compared to numerical calculations based on a scattering matrix formalism within the undepleted pump approximation. The extended two-dimensional photonic crystals etched into GaN, coupled with large non-linearities, is an appealing feature pointing towards the control and manipulation of light in photonic structures.

2:00 PM E7.2

III-Nitride Deep UV Photonic Crystals, Jagat Shakya, Kyoung H. Kim, Jingyu Lin and Hongxing Jiang; Physics, Kansas State University, Manhattan, Kansas.

Photonic crystals (PCs) have been fabricated on MOCVD grown different III-nitride structures. Triangular lattice arrays of holes with diameters ranging from 100 to 800 nm were patterned in a GaN layer using electron beam lithography and inductively-coupled-plasma dry etching. Current injected UV photonic crystal LEDs (PC-LEDs) revealed about 3 times enhancement in optical power over conventional wide-bandgap LEDs. The enhanced two-dimensional photonic crystal field constant and hole size. In comparison to the blue PC-LEDs with the fundamental field coupled into a resonant Bloch mode, while the second-harmonic field was not. Experimental second-harmonic intensities are successfully compared to numerical calculations based on a scattering matrix formalism within the undepleted pump approximation. The extended two-dimensional photonic crystals etched into GaN, coupled with large non-linearities, is an appealing feature pointing towards the control and manipulation of light in photonic structures.

2:00 PM E7.3

All-Optical switches based on intersubband transitions in GaN/AIGaN/AlGaN quantum well structures, Farhan Rana and William J. Schaff, ECE, Cornell University, Ithaca, New York.

We will present experimental and theoretical results for novel all-optical switches operating at wavelengths close to 1.55 μm and based on intersubband transitions in GaN/AIGaN/AlGaN multiple quantum well structures. These devices are currently used for all-optical signal processing and are expected to offer data rates beyond 80 Gb/s. Optical fiber based devices, although fast, require pulse energies of several tens of pJ for switching as a result of the small fiber nonlinearities [1]. Devices based on intersubband transitions in semiconductors (SOA) require small pulse energies, but they have slow carrier recovery time (a few tens of ps), which limits their performance to data rates less than 80 Gb/s [2]. By contrast, intersubband electron relaxation times in semiconductor quantum wells are less than 1 ps [3,4]. As a result, intersubband optical switches and large intersubband optical oscillator lengths, these devices are capable of switching speeds close to 1 Tbit/s while requiring pulse energies as low as 100 fJ, making them ideal for ultrafast all-optical signal processing on a chip.

We will present results on all-optical switches based on cross-phase modulation and cross-phase modulation in integrated GaN/AIGaN optical waveguides. We will show extensions to (between logical 1 and 0) better than 15 dB at data rates as high as 1 Tbit/s. The growth of GaN/AIGaN quantum wells on AIN and AlGaN buffer layers on sapphire substrates is an attractive solution to the strong effect of the surface recombination. The surface recombination velocities on the p-type GaN epitaxial surface are about 1.73 x 10^14 cm/sec making it difficult to control the modulation speed of UV LEDs, which could be very useful for many applications. The PCs fabricated on MOCVD grown AIN epitlayers, which can be used to manipulate light with wavelength as small as 200 nm, will also be discussed.

2:15 PM E7.4

The Ga-Nitride/air Two-Dimensional Photonic Quasicrystals, Wei Zhang, ZhiSheng Zhang, Jun Xu, Qi Wang, ZhiJian Yang, WeiHun Chen, XiaoDong Hu, XiLin Qin, GuoYi Zhang and DaPeng Yu; Physics, Peking University, Beijing, China.

Currently, the photonic crystal composed by quasicrystal structure attracts much interest. The photonic quasicrystals with high-order rotational and linear symmetries with large structural flexibility. It may possess photonic bandgaps and exhibit unique light behaviors, such as more isotropic light scattering, but also with a low direct energy fill factor and small angle rejections. It makes photonic quasicrystals promising for application in a variety of optical devices. However, few reports on the GaN-based 2D QPC can be found due to the big technical challenge in fabricating the required small scale. In this report, the fabrication of two-dimensional (2D) photonic 8-fold and 12-fold quasicrystals by means of focused Ga ion beam (FIB) milling is presented. The optical properties of the QPCs made on the GaN-based multiple quantum-well light emitters were investigated. The 8-fold and 12-fold air/GaN photonic quasicrystals were successfully fabricated by FIB milling using a high aspect ratio and flexible dry etching method with the advantages of masklessness, and direct writing for fine patterning. Under the fixed acceleration voltage of Ga ions at 30kV, the FIB etching rate of the 2D GaN-based photonic 8-fold and 12-fold quasicrystals was 8 nm/min. It makes photonic quasicrystals promising for application in a variety of optical devices. However, few reports on the GaN-based 2D QPC can be found due to the big technical challenge in fabricating the required small scale. In this report, the fabrication of two-dimensional (2D) photonic 8-fold and 12-fold quasicrystals by means of focused Ga ion beam (FIB) milling is presented. The optical properties of the QPCs made on the GaN-based multiple quantum-well light emitters were investigated. The 8-fold and 12-fold air/GaN photonic quasicrystals were successfully fabricated by FIB milling using a high aspect ratio and flexible dry etching method with the advantages of masklessness, and direct writing for fine patterning. Under the fixed acceleration voltage of Ga ions at 30kV, the FIB etching rate of the 2D GaN-based photonic 8-fold and 12-fold quasicrystals was 8 nm/min. It makes photonic quasicrystals promising for application in a variety of optical devices. However, few reports on the GaN-based 2D QPC can be found due to the big technical challenge in fabricating the required small scale. In this report, the fabrication of two-dimensional (2D) photonic 8-fold and 12-fold quasicrystals by means of focused Ga ion beam (FIB) milling is presented. The optical properties of the QPCs made on the GaN-based multiple quantum-well light emitters were investigated. The 8-fold and 12-fold air/GaN photonic quasicrystals were successfully fabricated by FIB milling using a high aspect ratio and flexible dry etching method with the advantages of masklessness, and direct writing for fine patterning. Under the fixed acceleration voltage of Ga ions at 30kV, the FIB etching rate of the 2D GaN-based photonic 8-fold and 12-fold quasicrystals was 8 nm/min. It makes photonic quasicrystals promising for application in a variety of optical devices. However, few reports on the GaN-based 2D QPC can be found due to the big technical challenge in fabricating the required small scale. In this report, the fabrication of two-dimensional (2D) photonic 8-fold and 12-fold quasicrystals by means of focused Ga ion beam (FIB) milling is presented. The optical properties of the QPCs made on the GaN-based multiple quantum-well light emitters were investigated. The 8-fold and 12-fold air/GaN photonic quasicrystals were successfully fabricated by FIB milling using a high aspect ratio and flexible dry etching method with the advantages of masklessness, and direct writing for fine patterning. Under the fixed acceleration voltage of Ga ions at 30kV, the FIB etching rate of the 2D GaN-based photonic 8-fold and 12-fold quasicrystals was 8 nm/min. It makes photonic quasicrystals promising for application in a variety of optical devices. However, few reports on the GaN-based 2D QPC can be found due to the big technical challenge in fabricating the required small scale. In this report, the fabrication of two-dimensional (2D) photonic 8-fold and 12-fold quasicrystals by means of focused Ga ion beam (FIB) milling is presented. The optical properties of the QPCs made on the GaN-based multiple quantum-well light emitters were investigated. The 8-fold and 12-fold air/GaN photonic quasicrystals were successfully fabricated by FIB milling using a high aspect ratio and flexible dry etching method with the advantages of masklessness, and direct writing for fine patterning. Under the fixed acceleration voltage of Ga ions at 30kV, the FIB etching rate of the 2D GaN-based photonic 8-fold and 12-fold quasicrystals was 8 nm/min. It makes photonic quasicrystals promising for application in a variety of optical devices.
light emitters. The microscopic fluorescence under UV light excitation and the electrical luminescence under current injection were measured from the devices to verify the proper operation of the cavity. The optical quality of the GaN/AlGaN PQC layers was assessed by planning the GaN/AlGaN PQC layers and examining the formation of the built-in tensile stress usually observed in AlGaN/GaN DBRs. This tensile stress, originating from the difference between the crystallographic parameters of GaN and Al,Ga$_{1-x}$Ga$_x$N alloys (up to 2.5%), is a key parameter for device fabrication as it usually leads to crack formation. Furthermore, lattice-matched AlInN layers do not introduce any new dislocations in the DBRs and the cavity region. Reflectivity and transmission measurements were carried out on a monolithic microcavity made of two AlInN/GaN DBRs with 35 (bottom) and 30 (upper) periods exhibiting a large stop-band of 30 nm resulting from the high refractive index contrast between AlInN and GaN layers. The cavity mode with a linewidth of 2 nm is clearly resolved. This linewidth corresponds to a cavity quality factor Q superior to 200, the highest value reported so far for a fully epitaxial nitride-based cavity. This result will be compared to theoretical expectations for such a structure. The effects on the cavity mode linewidth of the interface roughness in the Bragg mirrors, as well as the indium segregation in the AlInN layers will be discussed. Eventually, photoluminescence spectra will be presented and the optical properties (linewidth and oscillator strength) of the InGaN/GaN QWs required for active strong light-matter coupling in such a structure will be investigated.

4:15 PM E7.8

Crack-free Nitride-based Distributed Bragg Reflectors Growing on Patterned Substrates. Carsten Kranz, Stephan Figge, Sven Einfeldt, Claudia Roder, Jens Dennenmark and Detlef Rommel, Institute of Solid State Physics, University of Bremen, Bremen, Germany.

Light-high reflectivity distributed Bragg reflectors (DBRs) are of particular interest concerning the resonant cavity light-emitting diodes (RCLEDs) and vertical-cavity surface-emitting lasers (VCSELs). In this paper we report on the epitaxial growth of nitride-based DBRs with metal assisted molecular beam epitaxy (MAMBE) on GaN/sapphire template layers previously fabricated by metal-organic vapour-phase epitaxy (MOVPE). The DBRs consist of 42 nm thick GaN layers forming the high-index material and AlN (1.25 nm)/GaN (0.5 nm) superlattices (SLs) of 29.5 periods forming the low-index material. Due to the fact that the period of the SL is much shorter than the wavelength of the reflected light, the SL acts as a quasiterary alloy with a dispersion of Al(0.60/0.40)N. However, according to in-situ observation by reflection high-energy electron diffraction (RHEED), the surface roughness during growth of a SL-based DBR is reduced compared to a DBR structure where GaN layers of the same average Al content are used. The SL approach also provides an additional degree of freedom for reduction of the serial electrical resistance of doped DBRs by miniband formation and doping enhancement. As expected, these structures show a high density of cracks when grown on unpatterned substrates due to the tensile strain caused by the high lattice mismatch between the DBR and the GaN template layer. The formation of cracks can be widely suppressed when Indium as a surfactant is added during growth. A DBR with 17 Bragg periods grown under these conditions shows a peak reflectivity of 89% at 443 nm, while the stepband has a full-width at half maximum of 35 nm. Another approach for achieving crack-free areas on the surface is the use of a patterned substrate. Therefore, mesa of 25 μm × 25 μm size divided by 5 μm trenches have been etched from the MOVPE template layer by chemical assisted ion beam etching (CAIBE) prior to growth. In comparison, a part of the substrate has been left unstructured. DBR structures as described above were successfully deposited on these mesa but the formation of cracks and showed a sufficiently smooth surface according to RHEED. In contrast, the unstructured reference part was cracked. Reflectivities above 99% and microcavities with high quality factors are expected in the near future by a combination of both promising approaches, i.e. the use of Al as a surfactant and growth on patterned substrates. The chosen mesa size is sufficiently large for the preparation of a later VCSEL device that has a size of a few micrometers only.

4:30 PM E7.9

Electroluminescence Characteristics of GaN-Based Micro-Cavity Light-Emitting Diodes at a Cavity Thickness Below 1 μm. Tetsu Furi, Atsushi Hasegawa, Institute for Quantum Electronics and Photonics, Swiss Federal Institute of Technology, Lausanne, Vaude, Switzerland.

We report the growth over an entire 2 inch sapphire wafer of a crack-free monolithic nitride-based microcavity using highly reflective lattice-matched AlInN/GaN distributed Bragg reflectors (DBRs). This structure is the first step towards the demonstration of the light-matter interaction in nitrides and the fabrication of nitride vertical cavity surface emitting lasers (VCSELs). The optical cavity presented here is formed by a 3A/2 GaN cavity with two sets of InGaN/GaN quantum wells (QWs) with an emission peak centred at 405 nm at room temperature. Two AlInN/GaN DBRs with reflectivities in excess of 99% were used for the fabrication of this cavity. The use of the low index layer of a lattice-matched Al$_{1-x}$Ga$_x$N Alloy instead of GaN allows for the formation of the built-in tensile stress usually observed in AlGaN/GaN DBRs. This tensile stress, originating from the difference between the crystallographic parameters of GaN and Al$_{1-x}$Ga$_x$N alloys (up to 2.5%), is a key parameter for device fabrication as it usually leads to crack formation. Furthermore, lattice-matched AlInN layers do not introduce any new dislocations in the DBRs and the cavity region. Reflectivity and transmission measurements were carried out on a monolithic microcavity made of two AlInN/GaN DBRs with 35 (bottom) and 30 (upper) periods exhibiting a large stop-band of 30 nm resulting from the high refractive index contrast between AlInN and GaN layers. The cavity mode with a linewidth of 2 nm is clearly resolved. This linewidth corresponds to a cavity quality factor Q superior to 200, the highest value reported so far for a fully epitaxial nitride-based cavity. This result will be compared to theoretical expectations for such a structure. The effects on the cavity mode linewidth of the interface roughness in the Bragg mirrors, as well as the indium segregation in the AlInN layers will be discussed. Eventually, photoluminescence spectra will be presented and the optical properties (linewidth and oscillator strength) of the InGaN/GaN QWs required for active strong light-matter coupling in such a structure will be investigated.
Gallium Nitride is receiving a great deal of attention due to its opto-electronic and electronic properties. Typically, GaN layer is deposited on sapphire, SiC, and Si substrates by MBE, MOCVD or HVPE techniques. In this paper, a spin coating technique is presented to deposit GaN layer on glass or Si substrate. High purity and high quality lab-made GaN powder is the source material for this technique. GaN powder has a unique platy morphology. The nanoplate, plate dimension (a direction), is as high as 100. The plate’s size distributed from less than 1μm to more than 20μm. The purity of this lab-made GaN powder is higher than 99.9% from Glow Discharge Mass Spectrometry (GDMS) analysis. By using a colloidal dispersion, GaN particle can be successfully disaggregated and dispersed into water. Then the colloidal dispersion is spun on glass or Si substrates. The dispersant can be removed by annealing process at 500°C. After these processes, a uniform GaN layer is deposited on the substrate. XRD data shows the particles to be highly oriented. Different thicknesses of the layers have been produced by spinning multiple layers on substrates. XRD and TEM are used to characterize the structure of the deposited GaN layer. SEM images will be presented to show the GaN morphology and cross section of the GaN layer. The optical property is studied by Cathodoluminescence (CL) technique. Raman spectroscopy is used to determine the quality of the GaN layer.

**SESSION E8: Poster Session**
December 1, 2004


Resonant Raman scattering in GaN nanocrystallites of various morphologies was studied. The A(1LO) polar mode exhibited Pohlke-type resonant Raman scattering and its characteristics were found to depend weakly on the morphology of the crystallites. UV-laser heating and heat treatment in the porous media of the crystallites were found to drastically modify the Raman properties. Redshifts in the Raman spectra of ultrathin samples were observed and attributed to this thermal effect. Photoluminescence studies concurred with these findings. Ensemble temperatures of the order of 350 K were inferred from the electron-phonon interaction model. This result was verified via experiments of Raman scattering in the high temperature regime. For small ensembles that contain 20 crystallites, the laser-heating effect is nominal, and the Raman line shape is primarily Lorentzian. This is indicative of a phonon-lifetime broadening mechanism. Additionally, the frontier concentration of the nanocrystallites that was inferred from the phonon-phonon interaction was found to be significantly lower than in GaN films.

**E8.4** ALN Bulk Crystal Growth on SiC Seeds. Rahul Dalmau, Raoul Schlesser and Shatko Situr; Dept. of Materials Science and Engineering, North Carolina State University, Raleigh, North Carolina.

ALN bulk crystals were grown on on-axis and off-axis SiC seeds by sublimation of an ALN powder source. Physical vapor transport growth was performed in nitrogen atmosphere in a resistively heated reactor. On-axis, (0001) oriented 6H-SiC seeds were coated with an ALN layer that was intended to support preliminary decomposition of SiC seeds exposed to ALN vapor to promote two-dimensional growth of ALN. Inch-sized bulk ALN layers between 0.1–3 mm thickness were obtained at seed temperatures varying from 1850–2900°C and at a constant reactor pressure of 500 torr. XRD characterization evidenced that the ALN grew in the direction of the SiC seed. Cracks, which formed in the ALN layers due to the thermal expansion mismatch between ALN and SiC, were observed to decrease with increasing ALN crystal thickness. Cracks in the ALN were observed to propagate parallel to the seed surface for longer times due to...
The combined influence of AlN layer thickness and SiC substrate decomposition. These crystals were used to prepare polished wafers with 1-inch diameter as determined by EFM. Bulk AlN layers were analyzed by glow discharge mass spectrometry to determine contaminant levels, such as oxygen (300-1200 ppm wt), carbon (160-300 ppm wt), and silicon (130-200 ppm wt). The influence of substrate misorientation on AlN growth was also evaluated, and rough regions were performed on on-axis and 4° off-axis 6H-SiC, and 8° off-axis 4H-SiC seeds. Step-flow growth of oriented, single-crystal AlN was achieved on off-axis SiC without the use of an AlN epilayer. HRXRD rocking curves of the AlN showed typical FWHM around 200 arcsec, which was comparable to values for the SiC substrates. FWHM values as low as 18 arcsec have been observed. Crystals grown on off-axis seeds exhibited two distinct morphologies: flat regions with 100 nm half-plane of edge dislocations. We also analyzed by EFM. The influence of SiC seed quality and orientation, process parameters, and growth mode on the polarity and morphology of bulk AlN grown on SiC will be discussed. Optical, structural, and elemental characterization results will be presented.

**E8.5 TRANSFERRED TO E10.7**

**E8.6 Theoretical determination of the intrinsic free carrier mobility in AlGaN/GaN quantum wells**, Francesco Carosella², Marianne Germain² and Jean-Louis Farvacque¹. University des Sciences et Technologies de Lille, CNRS UMR 8008, Villeneuve d’Ascq, France; ²IMEC, Microsystems, Components and Packaging, Leuven, Belgium.

In the actual state of the art, AlGaN/GaN quantum wells transport properties are mainly determined by extrinsic scattering mechanisms such as dislocations or electrical interface roughness. Thus, the maximum free carrier mobility that can be expected in such structures remains for the moment experimentally unknown. The aim of this contribution is to determine theoretically the maximum mobility that can be expected in AlGaN/GaN quantum wells as soon as the free carriers are only submitted to intrinsic scattering mechanisms associated with phonons and the carrier-carrier interaction. In our model, we consider that the carrier-carrier collisions do not constitute by themselves a relaxation mechanism since two-bodies collisions conserve the momentum and the energy of the electron system. Thus, we assume that the free carriers act only through their contribution to the dynamical dielectric response of the material and, at least, through their collective behavior resulting into plasmaons which, when damped, constitute now a real relaxation mechanism. Following the analysis developed in the case of 3 dimensional system [3D] [1], the full scattering strength is connected with the imaginary part of the total material reversed dielectric function including the lattice and the free carrier contributions. This approach automatically includes the scattering of the corresponding associated wave functions and phonons and plasma particles. Using simple arguments, we, first, generalize the 3D Kim’s approach to the case of 2-dimensional multi subbands systems. Then, our model is applied on the quantum well potential which are numerically determined in the case of triangular quantum well potentials, with a procedure including exchange and correlation contributions, ii) on the numerical determination of the full dielectric function, whose zeros correspond to optical phonons, plasmaons, and their hybrid pseudo-particles. The numerical results show that relatively large intrinsic mobility versus carrier density are obtained. At room temperature, typical values are \( \mu = 2500 \text{ cm}^2/\text{Vs} \) for an areal carrier density \( n = 4 \times 10^{13} \text{ cm}^{-2} \) and around \( 3000 \text{ cm}^2/\text{Vs} \) for \( n = 22 \times 10^{13} \text{ cm}^{-2} \). We note however, that the full calculation strongly depends on the carrier wave functions and therefore on the choice of the potential shape describing the quantum well which may lead to other mobility values. Comparison of the present theoretical results with our previous experimental results [1] and discussion [12].


The recent years have seen the successful upscaling of production capacities to 24x2 inch reactors to supply the ever growing device market. This approach, however, is only feasible if processing pipelines are still able to cope with the increasing load and do not become the bottleneck of device processing. To offer flexibility to the device manufacturer’s options for increased production, we have developed the AIX 2600G3 HT for the growth of up to 8 inch wafers, effectively increasing the usable wafer area from 300 in² to 400 in² while decreasing the number of wafers in the processing pipeline from 24 to 8 when compared to the 24x2 inch configuration. The growth on 4 inch, however, requires special attention to effects of wafer bow and layer strain which originates either in the wafer itself or at the interface of the sapphire and the growing layer. While this effect is already present in larger wafers, it tends to be more severe as the wafer size is increased causing the wafer to lose contact to the MOCVD tool’s heated graphite susceptor when the device layers become thicker. Thus, in turn, can lead to temperature deviations across the wafer which are especially unfavourable in the growth of InGaN structures. To remedy these effects, careful engineering of the MOCVD tool along with extensive investigations on the properties of the wafer, its surface and miscut angles were conducted. The influence of the sapphire wafer bow and wafer thickness on the optical properties of the sapphire substrate was primary Al-polar (c+) but contained N-polar (c-) inclusions revealed in the X-ray rocking curves of the AlN showed typical FWHM around 200 arcsec, which was comparable to values for the SiC substrates; FWHM values as low as 18 arcsec have been observed. Crystals grown on off-axis seeds exhibited two distinct morphologies: flat regions with 100 nm half-plane of edge dislocations. We also analyzed by EFM. The influence of SiC seed quality and orientation, process parameters, and growth mode on the polarity and morphology of bulk AlN grown on SiC will be discussed. Optical, structural, and elemental characterization results will be presented.

**E8.8 The Reduction of Threading Dislocations in GaN: A Study by Transmission Electron Microscopy, Ranjan Datta, Menno J. Kappers, Jonathan S. Barnard and Colin J. Humphreys; Department of Materials Science and Metallurgy, University of Cambridge, Cambridge, United Kingdom.**

The reduction of threading dislocations (TDs) in GaN is important as TDs act as non-radiative recombination centers and generally reduce the luminescence efficiency of GaN-based optoelectronic devices. We have used an in-situ ELO technique by depositing a non-uniform SiNx mask (as revealed by STEM-EDX analysis) using silicon and ammonia gas, either on a sapphire substrate or on a GaN pseudo-substrate. The effect of several growth parameters such as the V/III ratio, pressure, temperature and the duration of the Si/N treatment on the morphology, structural quality and TD density were investigated. To start the epilayer growth with a low V/III ratio gives rise to predominantly 3D growth, forming islands with multiple inclined facets and a vanishing top (0001) facet. An increased V/III ratio enhance the lateral growth, and with inclined -2112 facets along with a flat top (0001) facet are observed. The duration of the Si/N treatment and the low V/III ratio growth regime are optimized in order to reduce the TD density down to \( \times 10^{12} \text{ cm}^{-2} \) measured from plan-view TEM images. It is observed that TDs bend through 90° by inclined side facets. The role of atomic ledges moving across inclined facets which are responsible for bending the line of the TDs is being explored. The step movement of dislocations is also observed, and is explained in terms of dislocation climbing, assisted by the continuous incorporation of vacancies through the growing side facets and diffusion to the core of the extra half plane of edge dislocations.


GaN-based intersubband transition (ISTB) is of great interest for ultraviolet optical device applications. The ISTB communication wavelengths have previously been reported and the communication relaxation time has been measured at considerably less than 1 ps. Since the ISTB occurs only for TM-polarization, the background polarization-dependent loss for the TM-polarization in a waveguide structure is a key parameter for device design. The propagation characteristics of GaN waveguides, however, have yet to be fully clarified. In this study, after considering that ISTBs have been achieved at optical communication wavelengths only with MBE-grown GaN ridge waveguides, we investigated the polarization dependent loss (PDL) for GaN ridge
waveguides grown by MBE under various growth conditions such as nitridation temperature, Si-doping, insertion of multiple intermediate layers (MIL), and growth on MOCVD-grown GaN with a thickness of 0.8 µm. All samples were grown on a sapphire substrate and were 2 µm in total thickness. The ridge width, height, and length were 2 µm, 1 µm, and 1 mm, respectively. PDLS were evaluated with a CW laser source at a wavelength of 1.56 µm. The transmittance for TM-polarization were greater than those for TE-polarization, and the PDL strongly depends on the growth conditions. The PDL was -15 dB for the sample with a nitridation temperature of 540 °C whereas it was -18 dB for the sample nitrided at 300 °C and inserted with MIL. On the other hand, it worsened to -22 dB for the sample nitrided at 300 °C and doped with Si at 3x10^19 cm^-3. We believe that the edge dislocations were a result of the interaction of the epitaxial layer and the residual carriers and acted as a polarizer. Since the nitridation temperature and MIL structure affected the edge dislocation density, the PDL was different among those samples. When Si was doped, the dislocations were more significant, and the possibility of the formation of Mg segregation was increased. From the Hall measurement, the dislocation densities were estimated to be 2.7x10^10 cm^-2 for the nitridation at 540 °C and 3.3x10^10 cm^-2 for 300 °C. Therefore, the PDL is considered to be proportional to the number of the dislocation density. Finally, the PDL for the sample re-grown on MOCVD-grown GaN, in which the dislocation density was expected to be in the order of 10^10 cm^-2, drastically improved to -1.5 dB. In conclusion, an MBE-grown GaN ridge waveguide was found to have a large PDL, which was due to edge dislocations with a density in the order of 10^10 cm^-2. The re-growth on MOCVD-grown GaN, however, decreased the dislocation density and significantly improved the PDL. The result is encouraging with respect to producing ultrafast optical devices utilizing the ISBT. This work was performed under the supervision of the Femtosecond Technology Research Association (FESTA), which is supported by the New Energy and Industrial Technology Development Organization (NEDO).

E8.10 Microstructure of High P-Type Doped GaN Sub-Contact Layers for Low-Resistivity Contacts. Roland Kroeger1, Jens Denneberg1, Stephan Figge1, Tim Boettcher2, Detlef Hommel2, Eliana Kaminski2 and Anna Pietrowska3; 1Institute of Solid State Physics, University of Bremen, Bremen, Germany; 2Institute of Electronic Technology, Warsaw, Poland.

The difficulty to realize low-resistivity contacts on GaN-based devices grown by metal organic vapor phase epitaxy can be overcome by depositing a thin highly Mg-doped sub-contact layer. However, the formation of pyramidal defects, which act as dopant traps and probably as non-radiative recombination centers, has to be avoided. The defects form, as was previously shown [1], if a critical Mg to group III molar ratio of 0.02 is exceeded. In this case a defect-free zone can be observed due to the segregation of Mg. The extension of this zone depends itself on the flow ratio. Based on the knowledge of this dependence sub-contact layers were grown with different Mg to group III ratios. Flow ratios for PE- and MOCVD-grown GaN layers were 0.053 and 0.025, respectively. A contact resistance of 0.035 a specific contact resistance as low as 2x10^-5 cm^2 could be obtained. Below and above this value for the flow ratio the resistance increased up to almost two orders of magnitude, since on the low flow ratio side the contact was not sufficient and on the high flow ratio side the onset of Mg related defect formation took place. A microstructural analysis of the sub-contact area by means of transmission electron microscopy showcased for the low-resistivity contact a smooth interface and no pyramidal defects in the highly Mg-doped GaN surface during a post-growth anneal step. These findings indicate that a smooth and highly p-type doped surface is beneficial for an improved current flow through GaN-based devices. [1] S. Figge, R. Kroeger, T. Boettcher, P.L. Ryder, and D. Hommel, Appl. Phys. Lett. 81, 4748 (2002).


The development of vertical devices with low-leakage currents deposited on SiC represents an important challenge in the development of III-Nitride materials. Threading dislocations have been identified as defects that contribute to such leakage. We have recently presented results in which GaN was grown on an AlN nucleation layer on a 4H-SiC mesa-patterned substrate that contain regions that are free of surface steps. Cross-sectional transmission electron microscopy (XTEM) samples of individual SiC mesa with MOCVD-deposited GaN films have been fabricated using focused ion beam (FIB) milling. Our XTEM observations indicate that in addition to threading dislocations with a dislocation density of 5x10^6 cm^-2, heteroepitaxial GaN/SiC growth (8 x10^7/cm²), the nucleation layer and subsequent GaN films grown on the mesa contain sufficiently few screw or mixed dislocations that their combined density at the film surface was measured by AFM to be on the order of 106/cm². This is particularly promising for vertical devices as screw dislocations have been identified as leakage paths [Hsu et al., APL 81, 79 (2002)]. The tendency of lateral a-type dislocations (i.e those with a 1/6<210> Burgers vector) to annihilate at the 100 nm-thick AlN nucleation layer and early in the subsequent GaN growth was also observed. These observations led to the conjecture that the presence or absence of substrate surface steps may influence the core structure of threading dislocations nucleating at the substrate/nucleation layer interface. Dislocations nucleating in the absence of SiC substrate steps may differ from dislocations nucleating on a step. Dislocations nucleated on step-free surfaces may have a core structure that promotes dislocation mobility resulting in strain-driven dislocation recombination and annihilation. Indeed, because of the possible difficulty of nucleating on step-free surface (due to the absence of stress concentrations and dangling bonds) dislocations forming in such an environment may require greater mobility so that such kinetic dislocations are able to compensate for impeded nucleation. Low coverage growth experiments of AlN on SiC were performed to determine the dependence of the core type and subsequent mobility on the presence or absence of unstepped surfaces. High-resolution transmission electron microscopy studies of the nucleation behavior of threading dislocations nucleating at the interface between the 4H-SiC surface steps will be used to elucidate the role of steps in the development of screw and mixed type dislocations. We have recently developed a model for strain relief (due to the presence of surface bounding the film grown on the mesa) and will consider the contribution of fewer elastic constraints on dislocation annihilation.

E8.12 Cathodoluminescence of Praseodymium Doped Amorphous AlN, GaN, and Turbostratic BN. Muhammad Maqbool and Martin E. Kordesch, Department of Physics & Astronomy, Ohio University, Athens, Ohio.

Praseodymium (Pr) doped aluminum nitride (AlN), gallium nitride (GaN) and boron nitride (BN) thin films deposited on Si(111) substrates are studied with cathodoluminescence. AlN:Pr and GaN:Pr films are deposited at 77 K and room temperature respectively while BN:Pr films are grown at 800 K by reactive magnetron sputtering, using 100-200 Watts RF power, 5-15 mTorr nitrogen. Metal targets of aluminum and boron with praseodymium and a liquid target of gallium with solid praseodymium were used. The dominant peaks observed in the visible range result from the following transitions: in AlN:Pr at 498 nm, 507 nm and 652 nm in AlN:Pr, 3p(2)1P03H2, 3p(2)1P13H3 and 3p(2)1P33H5 transitions with peaks at 488 nm, 621 nm and 650 nm in GaN:Pr, and from 3p(2)1P03H0, 3p(2)1P23H0 and 3p(2)1P33H0 transitions with peaks at 488 nm, 544 nm, 628 nm and 654 nm in GaN:Pr transitions. In AlN:Pr, 3s(2)1S03P2 and 3s(2)1S03P0 transitions with peaks at 335 nm and 383 nm are observed in AlN:Pr at 335 nm and 383 nm from 3s(2)1S03P2 and 3s(2)1S0 transitions which are not observed in GaN:Pr and BN:Pr films.

E8.13 Micro-Characterization of GaN and AlGaN on Si(001). Fabian Scholze, Till Riemann, Armin Dadgar, Juergen Blassing, Juergen Christen and Alois Kroth, Institute of Experimental Physics, Otto-v-Guericke University Magdeburg, Magdeburg, Germany.

For the integration of GaN-based devices with standard silicon technology, high-quality group III-nitride layers have to be grown on the Si(001) surface of silicon. While the issues of lattice mismatch and crack formation have been successfully solved for growth of nitrides on Si(111), the non-equivalent lattice symmetries of both materials still remain a challenge in the epitaxy of nitrides on Si(001). We present a systematic study of GaN and AlGaN layers grown by metal organic vapor phase epitaxy (MOVPE) on Si(001) and, for comparison, on Si(111) substrates. Prior to 300nm GaN or AlGaN (Al:0=0.1) growth, AlN buffer layers were deposited. Growth temperature, layer sequence, and thickness of these buffers were methodically varied. According to X-ray diffraction, two different orientations of the (Al)GaN crystallites with respect to the Si(001) surface were realized by variation of the buffer layer design: GaN grows in [110] oriented on the Si(001) substrate with four rotational alignments, if a low temperature (530°C) AlN interlayer is used. In contrast, the use of a high temperature AlN (HT-AlN) seed layer results in exclusive c-orientation of the (Al)GaN crystallites. Tabular data show rotational alignments of the GaN and AlGaN a-plane are...
observed. The impact of the buffer on the crystallographic orientation directly emerges in the morphology of the GaN and AlGaN layers as seen in high-resolution scanning electron microscopy (HRSEM) images. For the growth on HT-AIN obtaining growth on low-temperature buffers, GaN micro-crystals are formed which exhibit rectangular in-plane facets. In contrast, growth on HT-AIN gives hexagonal top facets. Here, AlGaN forms a fully coalesced and atomically flat surface with a high density of grain boundaries (GBs) by incorporating crystalline steps. The microscopic optical properties are assessed by spectrally resolved cathodoluminescence microscopy (CL). While GaN on Si(111) is always characterized by the dominant emission of the donor bound exciton (D0X), GaN grown in the same epitaxial run on Si(001) shows strong lateral fluctuations of the dominant emission process, involving (D0X) as well as several impurity related emissions. Large GaN micro-crystals on Si(001) are always characterized by intense excitonic CL, providing their high structural quality, and optical quality. For AlGaN on HT-AIN buffer layers, the full width at half maximum (FWHM) of integral CL spectra increases from 45meV to 120meV when using Si(001) instead of Si(111). However, local CL spectra of individual AlGaN nano-crystals consist of sharp (FWHM=35meV) lines corresponding to distinct Al-concentrations. The lateral fluctuation of the CL peak position, reflecting the laterally varying Al-concentration, is quantitatively evaluated.

**ES.14** Characterization of P-type Dopants in III-Nitrides by SIMS. Richard S. Hockett*, Patrick Van Liere*, Chuncheng Tian†, Pablo Fernando Cerdeira‡, Eliermes A. Meneses‡, 1Department of Materials Science and Engineering, Lehigh University, Bethlehem, Pennsylvania; 2Department of Physics, Lehigh University, Bethlehem, Pennsylvania. Recent developments in the III-Nitrides have prompted the expansion of our capabilities for the characterization of these materials by Secondary Ion Mass Spectrometry (SIMS). The list of elements of interest, be it for the study of impurity concentration, has increased steadily. Also, the size of device structures have shrunk and consist of more complex layer structures. Too meet these requirements we have made two improvements. The accuracy of concentration measurements for p-type dopants Be, B, Mg, Zn, and Fe based has been improved by developing a new suite of Relative Sensitivity Factors (for GaN and AlGaN). Small area depth profile analysis has been improved by optimizing a Cameca IMS-6f SIMS instrument to be able to profile p-type dopants in areas as small as 30 x 50 microns. This allows for the characterization of individual die and processed wafers. The Relative Sensitivity Factors were derived from implanted GaN and AlGaN epitaxial layers on sapphire wafer pieces. The doses were calibrated from the implanter and cross checked with witness pieces against our extensive library of Si reference standard materials. The Al mole fraction was determined by XRD and RBS. To illustrate the ability to profile the p-type dopant profile in a small area, a blue LED was deposited on a Si wafer for SIMS characterization. III-Nitrides, in particular, suffer from defects due to lattice mismatch with underlying layers or strain introduced during the growth process. These defects, combined with chip processing, can cause spatial localization of dopants due to the shallow depth resolution which in turn limits the usefulness of the SIMS data to evaluate the diffusion of dopants or layer sequence. In order to minimize the effects from the surface roughness, the LED was polished on an Allied Tech Products, Inc. MultiPolo tool with Dia-Grid Diamond Discs. The data including the Mg doping profile will be presented. The Al and In traces indicate the position of the AlGaN and InGaN layers including the three InGaN quantum wells (QW) and their interfaces.

**ES.15** Strong Room Temperature 510 nm Emission from Cubic InGaN Quantum Wells. Shunfeng Li*, Donat J. Derenzo†, Steven R. K. Jayasekera‡, Jennifer L. Savoy*†, Shyam Prabhakaran*, Alexander S. Kuchinsky*, Charles J. Collins*, A. V. Sampath*, G. A. Garrett†, W. L. Sarney*, H. Shen†, M. Wraback†, A. Y. Nikolaev†, G. S. Cargill†, and V. Deroko*, 1Department of Physics, Lehigh University, Bethlehem, Pennsylvania, 2Department of Physics, Lehigh University, Bethlehem, Pennsylvania. Enhanced radiative efficiency associated with carrier localization due to compositional fluctuations, often in the presence of high dislocation densities, has been exploited in the development of InGaN-based light emitting diodes (LEDs). This localization effect is sought in the AlGaN material system in hope of producing efficient, deep UV LEDs. We report the observation of intense, long-lived, room temperature photoluminescence (PL) from localized states in AlGaN alloys. The samples are 1-2μm-thick AlGaN/GaN QW heterostructures grown by plasma-assisted molecular beam epitaxy on sapphire (0001) substrates with a 250nm low temperature AlN nucleation layer. Transmission electron microscopy measurements suggest a defect density greater than 10^12 cm^-2. The films were studied by variable temperature PL, reflectivity, scanning cathodoluminescence (CL), and time-resolved PL (TRPL). Room temperature PL shows intense emission that is significantly red-shifted, 300-500meV, from the band edge and red-shifted peak (250ps) and the band edge peak (50ps) are comparable to those seen in thick, low defect density HVPE GaN templates and conventional GaN on sapphire, respectively, and suggest that the red-shifted PL emanates from the recombination of carriers in localized states. TRPL at the red-shifted energy also shows a pump intensity dependent initial rise time, corresponding to the transfer of carriers to these localized states form the band edge, which decreases from 35ps to 5ps as the pump intensity is increased by more than an order of magnitude and saturates at high pump intensity. The saturation of the localized peak is accompanied by a corresponding large increase of time zero signal in the band edge peak. From these observations, we suggest that a spatial localization effect enhances the luminescence efficiency by inhibiting movement of carriers to nonradiative sites despite the high defect density.

**ES.16** Intense, Long-Lived, Room Temperature Photoluminescence from Localized States in AlGaN Alloys. Charles J. Collins*, A. V. Sampath*, G. A. Garrett†, W. L. Sarney*, H. Shen†, M. Wraback†, A. Y. Nikolaev†, G. S. Cargill†, and V. Deroko*, 1Department of Materials Science and Engineering, Lehigh University, Bethlehem, Pennsylvania; 2Department of Physics, Lehigh University, Bethlehem, Pennsylvania. High-Quality Thin GaN Layers Directly Grown on Sapphire by HVPE. Dennis Martin, Jerome Napieralski, Raphiel Butte, Nicolas Grandjean and Marc Ilegems; Swiss Federal Institute of Technology, Lausanne, Switzerland. Due to the lack of GaN substrates, III-V nitride optoelectronic devices, such as light emitting diodes, have to be grown on highly mismatched substrates like sapphire. This leads to a defective area near the GaN/sapphire interface and to threading dislocations propagating into the whole GaN epilayer. The dislocation density can however substantially be reduced by increasing the thickness of the GaN seed layer and the substrate temperature. Recent developments in the III-Nitrides have prompted the expansion of our capabilities for the characterization of these materials by Secondary Ion Mass Spectrometry (SIMS). The list of elements of interest, be it for the study of impurity concentration, has increased steadily. Also, the size of device structures have shrunk and consist of more complex layer structures. To meet these requirements we have made two improvements. The accuracy of concentration measurements for p-type dopants Be, B, Mg, Zn, and Fe based has been improved by developing a new suite of Relative Sensitivity Factors (for GaN and AlGaN). Small area depth profile analysis has been improved by optimizing a Cameca IMS-6f SIMS instrument to be able to profile p-type dopants in areas as small as 30 x 50 microns. This allows for the characterization of individual die and processed wafers. The Relative Sensitivity Factors were derived from implanted GaN and AlGaN epitaxial layers on sapphire wafer pieces. The doses were calibrated from the implanter and cross checked with witness pieces against our extensive library of Si reference standard materials. The Al mole fraction was determined by XRD and RBS. To illustrate the presence of thermally activated transport into regions of the sample characterized by the longer wavelength emission. Room temperature scanning CL images that monitored the red-shifted peak revealed spatial non-uniformity similar to that observed in Al(In)GaN alloys and attributed to compositional fluctuations and structural disorder. The films were studied by variable temperature PL, reflectivity, scanning cathodoluminescence (CL), and time-resolved PL (TRPL). Room temperature PL shows intense emission that is significantly red-shifted, 300-500meV, from the band edge and red-shifted peak (250ps) and the band edge peak (50ps) are comparable to those seen in thick, low defect density HVPE GaN templates and conventional GaN on sapphire, respectively, and suggest that the red-shifted PL emanates from the recombination of carriers in localized states. TRPL at the red-shifted energy also shows a pump intensity dependent initial rise time, corresponding to the transfer of carriers to these localized states form the band edge, which decreases from 35ps to 5ps as the pump intensity is increased by more than an order of magnitude and saturates at high pump intensity. The saturation of the localized peak is accompanied by a corresponding large increase of time zero signal in the band edge peak. From these observations, we suggest that a spatial localization effect enhances the luminescence efficiency by inhibiting movement of carriers to nonradiative sites despite the high defect density.
on sapphire substrate and benefit of a well-established two-step growth procedure. Furthermore the in situ growth monitoring by means of lenses and cameras has been advanced by optimizing the GaN material quality. However the MOVPE growth rate is rather low (typically 2-3 μm/hr), which is time consuming when aiming at fabricating thick GaN templates. As a consequence, the seed layer of GaN quasi-substrates is generally deposited by MOVPE before thickening by hydride vapor phase epitaxy (HVPE). HVPE allows to reach growth rate up to 100 μm/hr, which is a key advantage over MOVPE for GaN quasi-substrate production. At the present time there is no clear evidence of high-quality growth directly on sapphire but there is a strong interest in establishing a whole HVPE process aiming at reducing the fabrication cost of GaN quasi-substrates. In this work, we use in situ reflectivity measurements to optimize the HVPE growth of GaN directly on sapphire. The growth procedure consists in a low temperature nucleation layer deposited at 600°C followed by a re-crystallization step at 1050°C before the growth of the GaN layer at high temperature. We show that GaN templates of crystalline and morphological quality comparable to what is obtained by the MOVPE technique can be produced by HVPE. In particular, we demonstrate that the polarity of the GaN epilayers is a key parameter affecting the morphological quality of the surface. Ga-polarity leads to smooth surfaces (rms = 0.3 nm), while N-polar layers exhibit flat hexagonal truncated pyramids. The optimization of the nucleation step, in particular the control of the layer polarity, has been achieved following the evolution of the reflectivity measurements. The structural properties of a 6 μm thick GaN layer (Ga polarity) have been characterized by x-ray diffraction. The ω-scan linewidths are 281 arcsec (0002) and 201 arcsec (20-24) respectively. The dislocation density, estimated from cathodoluminescence spectra is 1x10^8 cm^-2. These characteristics compare well with MOVPE grown GaN epilayers and demonstrate that high-quality GaN thin films (<10 μm) can be fabricated by HVPE.

ES.18 High Pressure Annealing of HVPE GaN Free-Standing Films: Redistribution of Defects and Strain. Tanya Paskova', Tadeusz Suski2, Michael Bockowski2, Plamen Paskov2, Vanya Darachcová1, Bo Monemar1, Filip Tuomisto3, Kimmo Saarinen3 and Pierre Gibart1; 1IFM, Linkoping University, Linkoping, Sweden; 2Unipress, Polish Academy of Sciences, Warsaw, Poland; 3Helsinki University of Technology, Helsinki, Finland.

Free-standing GaN films grown by hydride vapor phase epitaxy (HVPE) are currently the most promising substitute of the native bulk nitride substrate, because of the difficulties in the growth of bulk GaN. Free-standing GaN wafers have been demonstrated by several groups and are even commercially available recently. However, a critical remaining question is the high nonuniform distribution of dislocations, impurities, native defects and strain along the thickness often leading to wafer bending and cracking. The high-pressure annealing as an important tool in the nitride research is expected to lead to redistribution of the defects and to a change of electrical, optical and structural parameters of the as-grown GaN films. GaN films were grown on sapphire using a two-step lateral overgrown metalorganic chemical vapour deposition GaN template. The selected samples for this study were crack-free GaN self separated samples from the sapphire substrate. Four free-standing HVPE-GaN samples have been annealed at high pressure of 10 kbar for 1 hour in temperature range from 1150 to 1450°C. We used photoluminescence, infrared ellipsometry and positron annihilation spectroscopies, as well as Raman scattering and high resolution x-ray diffraction to investigate the defect and strain redistributions before and after the annealing. We find a significant difference in the PL spectra of the as-grown and annealed free-standing films, particularly an increase of the strain in the Ga-face was accompanied by an increase of the second donor bound exciton and the defect emission intensities at 2.9 eV. The analysis aiming to reveal the impact of the high-pressure high-temperature annealing on the defect distributions and their relation to the curvature of the free-standing GaN films.

ES.19 Spectral Properties of InGaN/GaN-Structures Grown by MOVPE on Si(111) Substrates. Andrea Strittmatter1, E. Reissmann1, D. Bimberg1, T. Riemann2 and J. Chrzan2; 1Technical University Berlin, Institute of Solid State Physics, Sekr. PN 5-2, Berlin, Germany; 2Otto-von-Guericke University Magdeburg, Inst. of Experimental Physics, Magdeburg, Germany.

Non-planar Si(111) substrates are used in order to reduce the threading dislocation densities of GaN buffer layers in a non-interrupted epitaxial lateral overgrowth ELO process. This technique is potentially attractive for electronic and optoelectronic device applications since electrical and optical properties can be improved. In this contribution we present investigations on the spatial dependence of the luminescence properties of InGaN/GaN-stacks grown on top of such defect reduced GaN matrices. The Si(111) substrates were pre-patterned in an array of 6 μm wide and 2.5 μm deep grooves of perfect square profile, separated by 4.5 μm wide ridges, oriented along the Si[1-10] direction. The GaN buffer and finally the InGaN/GaN MQW are subsequently grown by metal organic chemical vapor deposition. The luminescence spectra emitted from the InGaN/GaN structures are dependent on the spatial position on a μm length scale. Besides local variations of the InGaN luminescence the different local optical modes surrounding the active layers have to be regarded. Since the bottom interface of the lateral overgrown region is connected to the optically more dense medium Si, there is an inherent difference in the phase contrast for the two principal regions. However, due to the perfect boundaries of the laterally grown part of the structures, the optical matrix is extended to the media in the grooves which are air/GaN/Si as well and contributes another 2.5 μm vertical cavity length. This leads to more and more dense Fabry-Perot oscillations which are overlapped with the Gaussian luminescence distribution originating from the active region. Spatially resolved cathodoluminescence spectroscopy is used to distinguish between the two different regions. Indeed, the CL spectra taken from the laterally grown layers show more Fabry-Perot oscillations than those taken from the coherent grown regions on top of the Si ridges. Furthermore, cathodoluminescence wavelength images exhibit fluctuations of the absorption peak wavelength which is attributed to the variation of the air gap inside the grooves leading to varying spectral positions of the cavity modes. Simulations using optical transfer matrices unveil a relatively strong sensitivity of the optical mode distribution to the height of the air gap.

ES.20 Comparison of the Effect of GaFace Layer Thickness on 2DEG Carriers Concentration in Si-face/GaN Heterostructure. Wenfei Wang1,2, Marianne Germain1, Joff Derlyun1, Ingrid Dewolf1, Dominique Schreurs1,2, Wouter Rathorehn1, Johan Das1, Ralf Vandermassen1 and Gustaf Bergström1,2; 1MCP, IMEC, Leuven, Belgium; 2E.E., K.U.Leuven, Leuven, Belgium.

To improve the power performance of AlGaN/GaN High Electron Mobility Transistors (HEMTs), thin insulating layers are added between the gate contact and AlGaN top layer. A trade-off between loss of transconductance and increased gate-voltage swing, as well as decreased gate leakage current is aimed at. We have investigated three different oxides and SiO_N as a function of layer thickness and the impact they have on the carrier concentration of the two-dimensional electron gas, which is formed at the interface of AlGaN/GaN due to the strong spontaneous and piezoelectric polarization effect in GaN material system. The surface charge at the top AlGaN layer has a strong influence on the carrier concentration. The AlGaN layer is sensitive to atmospheric conditions and surface treatment, that thin films of oxide or nitride can act to modify this surface charge. We assume that the processing does not alter the surface charge density, so the 2DEG carrier concentration can be extracted from the Capacitance-Voltage characteristics. A large number of samples were measured in order to obtain reliable statistics. These results were also confirmed by Hall measurements. All of the oxides of Al, Ta and Si show that the 2DEG carrier concentration decreased with increasing thickness of the respective oxide layers between the gate and AlGaN layer. On the other hand, the 2DEG carrier concentration increased strongly with increasing SiO_N layer thickness, varying from 0 to 10 nm. An elementary polarization model was used to fit the behavior for all materials and thicknesses leading to quantitative results. The fitting suggests that the effect of the oxides and SiO_N on the 2DEG carrier concentration can be explained by the differences between these thin films with respect to charge accumulation at the AlGaN/insulator interface. Furthermore, Raman spectroscopy shows that no strain is involved in case oxides are used, but high temperature deposited SiO_N-in-situ shows strikingly interesting behavior, that it adds more strain to AlGaN/GaN heterostructure. This increase in piezoelectric polarization in AlGaN top layer and then increases the 2DEG carrier concentration.

ES.21 Partial Dislocations in Wurtzite Structure GaN. Rong Liu1, Fernando A. Ponce1, Changing Chen2, Jinwei Yang2 and M. Asif Khan2; 1Dept. of Physics and Astronomy, Arizona State University; Tempe, Arizona; 2Dept. of Electrical Engineering, University of South Carolina, Columbia, South Carolina.

Epitaxy of GaN along the [1-10] direction (a-plane growth) is of much current interest mainly because of the absence of polarity effects.
when compared with c-plane growth. The microstructure for a-plane growth is different from the standard c-plane growth. In this new geometry, there is no critical slip system (parallel to the GaN growth front), resulting in the generation of high densities of partial dislocations and stacking faults. We present a detailed study of the nature of partial dislocations for GaN layers grown by OMVPE on r-plane substrates using high resolution x-ray topography (HRTXD). The partial dislocations follow \( <1-100> \) directions, with an inclination of 30 degrees with respect to the \([11-20]\) growth direction. Electron diffraction contrast analysis shows that the Burgers vector of the partial dislocation is \( 1/3<1-100> \), parallel to the dislocation lines. Stacking faults are observed to form well-defined jogs along a-planes. The formation of these defects is believed to be related with the evolution of surface morphology during the growth process.

E8.22 Abstract Withdrawn

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Single crystal GaN substrates are a more reliable, efficient and low cost alternative to sapphire and SiC substrates that are currently being used for developing nitrile based devices such as LEDs, high power FETS and laser diodes. GaN growth by two techniques are investigated here: in ammonothermal growth (analogous to hydrothermal growth which is commonly used for quartz), using potassium and lithium amide as mineralizers and GaN powders and vapor grown polycrystals as nutrients, thick GaN single crystal layers have been grown on both faces of (0001) HVPE GaN seeds in nickel based autoclaves. In GaN sublimation growth, Ga is transported under a temperature gradient in an atmospheres from a GaN powder source to the sapphire substrate which has a 3-6 micron GaN epilayer deposited on it. Synchrontron white beam x-ray topography (SWBXT) was initially used to image the defect structures in the layers. High resolution x-ray diffraction experiments were also performed on the samples to obtain reciprocal space maps from the ammonothermal grown layers and the HVPE seed in case of ammonothermal grown samples and from the vapor phase grown layers and CVD deposited epilayers in case of sublimation grown samples. From these experiments, tilt and mismatch information between the layers and overall strain data can be obtained. These results will be discussed with respect to the growth conditions.


Balaji Raghothaman\(^{1}\), Michael Dudley\(^{1}\), Rafael Dalmau\(^{2}\), Buguo Wang\(^{2}\), Phanikumar Konakapaka\(^{3}\), Huaqiang Wu\(^{3}\), Michael Spencer\(^{2}\) and David Bliss\(^{1}\), \(^{1}\)Materials Science & Engineering, Stony Brook University, Stony Brook, New York.

For nitrile based devices such as LEDs, high power FETS and laser diodes, single crystal substrates of AIN are highly desirable. While the sublimation technique is suitable for growing bulk AIN crystals, appropriate seeds are also necessary for growing large diameter oriented boules. 4H- and 6H-SiC substrates which are readily available commercially can potentially be implemented as seeds for bulk AIN growth. However, issues regarding SiC decomposition at high temperatures, thermal expansion mismatch, single crystal growth, etc. need to be addressed. Towards this end, a series of growth experiments have been carried out in a relatively heated reactor using on and off-axis 4H- and 6H-SiC substrates as seeds for AIN growth from the vapor phase. Several hundred microns thick AIN layers have been grown under different growth conditions. Synchrontron white beam x-ray topography (SWBXT) has been used to map the defect distribution in the grown layers and high resolution tri-axial x-ray diffraction (HRXRD) experiments were carried out to record reciprocal space maps from which tilt, mismatch and strain data can be obtained. These results are analyzed with respect to the growth conditions in order to gain a better understanding of this growth process.
In this paper, we report on novel results on highly doped p-type GaN layers and AIGaN/GaN heterostructures grown by hydride vapor phase epitaxy (HVPE) on sapphire substrates. For Mg-doped GaN layers, hole mobility as high as 80 cm^2/V·s was measured using conventional van der Pauw Hall effect characterization performed for p-type doped layers and structures fabricated on highly electrically conducting p-type GaN and sapphire substrates. For Mg-doped GaN layers, hole mobility as high as 80 cm^2/V·s was measured using conventional van der Pauw Hall effect characterization performed for p-type doped layers and structures fabricated on highly electrically conducting p-type GaN and sapphire substrates. The transport properties of these layers and structures will be discussed. High efficiency of the p-type doping may be related to the low background impurity concentration in GaN layers grown by HVPE. The growth of GaN layers by HVPE is an accepted method to produce GaN substrate materials, these results open an opportunity to develop the low resistive p-GaN substrates, both templates and free-standing for nitride device fabrication. We will also report on initial results obtained on highly electrically conducting p-type GaN and AIGaN/GaN heterostructures deposited on ZnO substrates. Concentration of N and Ga in the 1.0×10^17 – 1.0×10^18 cm^3 range was measured for as-grown Zn doped samples. The transport properties of these layers and structures will be discussed. High efficiency of the p-type doping may be related to the low background impurity concentration in GaN layers grown by HVPE, typically providing materials with concentrations of N and Ga in the 1.0×10^17 – 1.0×10^18 cm^3 range. Results of material characterization performed for p-type doped layers and structures using SIMS, x-ray diffraction, and AFM will be presented.

**Abstract Withdrawn**

**Impact of H₂-Preannealing of Sapphire Substrate on Crystallization of Pseudomorphic GaN/LT-AIN Buffer Layer.** Michinobu Tanaka,1,2 Motoki Ishii,1 Satoshi Kaniyama,1 Hiroshi Ameno,1 and Isamu Akasaki,1 1Single Crystal Division, Kyocera Corporation, Youkaichi, Shiga, Japan; 2Faculty of Science & Technology, 21st Century COE “Nano-Factory”, Meijo University, Nagoya, Aichi, Japan.

Success in the growth of device-quality GaN on sapphire substrate by metal organic vapor phase epitaxy (MOVPE) depends on the technology of the low-temperature-deposited (LT) buffer layer. The control of the substrate surface in the epitaxial growth is essential for obtaining high-quality layers. It is well known that, before the deposition of the LT-buffer layer, the sapphire substrate should be preannealed in a H₂ ambient, although the reason why preannealing is necessary is not well understood. We have reported that the preannealing temperature (T_a) should be higher than 900°C to obtain a high-quality LT-buffer layer, otherwise, polystalline GaN is grown. In this paper, the effect of H₂-preannealing on the crystallinity and the peak intensities of the LT-buffer layer, which is in direct contact with the sapphire substrate, is discussed. Sapphire is used as the substrate. An AlN layer is deposited as an LT-buffer on the substrate at 400°C by MOVPE. The H₂ preannealing is performed for 5 min at three different annealing temperatures, T_a = 400, 500, and 1200°C, before the deposition of the LT-AIN layer. As-deposited LT-AIN layers and LT-AIN layers which are annealed at 1050°C, which is the growth temperature of GaN, are compared. The LT-AIN layers are characterized by means of atomic force microscopy (AFM) and X-ray diffraction (XRD). No significant difference in surface morphology is observed among the layers deposited on the substrate preannealed at different T_a values. As a result of the symmetric XRD 2θ/ω scan of the LT-AIN layers deposited on the substrate with different T_a values, no diffraction peaks are observed when T_a = 1200°C. A relatively weak diffraction peak is observed when T_a = 900°C, and a markedly strong peak is observed when T_a = 900°C. The peak position is lower than 36°. In the case of the annealed LT-AIN layers, no peaks appear when T_a = 400°C, and the peak intensities at T_a = 900°C are much stronger than those of the as-deposited layers. The peak positions of these layers are shifted to approximately 30°, which indicates the existence of free-standing AlN. It is noted that the crystallinity of a LT-AIN layer, characterized on the basis of the XRD data and the peak position, shows a significant difference when T_a values varied. On a sapphire substrate preannealed at a low T_a, a LT-AIN layer with poor crystallinity (or an amorphous layer) is deposited. In the case that T_a is sufficiently high, the as-deposited LT-AIN layer is crystallized. LT-AIN is a highly elastic substrate that affects the shape of the substrate. The annealing process of the buffer layer not only improves the crystallinity, but also relaxes the lattice. T_a must be higher than 900°C to obtain GaN with high quality. Hence, the control of the sapphire surface by H₂ preannealing is necessary for the quality of a LT-AIN layer and the subsequently grown GaN epi-layer.
Low temperature luminescence of GaN sometimes exhibits a peak at 364 nm (3.42 eV). The origin of this peak is not well understood. The emission has been attributed to oxygen contamination [1] and to excitons bound to stacking faults [2]. Chung and M. Gershenzon, smooth SiC initial surface. However, the surface of the subsequently grown III-N layer is one of problems in this system. In this paper, we report on growth of GaN on 4H- or 6H-SiC (0001) Si-face substrates using elemental Ga and active nitrogen generated by an EPI unibulb rf-plasma source. First, we have tried 4H-SiC (0001) S0–off toward the [11–20] direction, which is a standard substrate in SiC device fabrication. Before the growth of GaN, ex-situ high-temperature gas etching or homoeptaxial growth was carried out, resulting in a smooth SiC initial surface. However, the surface of the subsequently grown GaN layer has wavy features with peak-to-valley height of 30 nm. Since the direction of the undulations is parallel to the misorientation direction, this feature must originate from the substrate misorientation. From the results of these experiments, it was found that step bunching and large faceting along [01–10] and [10–10] directions occurred during the growth of GaN. Lowering the growth temperature suppresses large faceting, and vice versa. This result is the first to directly correlate the presence of stacking faults to the 364 nm emission from GaN. The nature of stacking faults has been analyzed using different diffraction conditions. Stacking faults on a-plane have been observed at sites of basal-plane stacking faults. The dynamics of jog formation will be presented. [1] B.-C. Chung and M. Gershenzon, J. Appl. Phys. 72, 651 (1992). [2] Y. T. Rebane, Y. G. Shreter, and M. Albrecht, Phys. Stat. Sol. A 164, 141 (1997).

Abstract Withdrawn

Influence of Substrate Misorientation Angle and Direction in Molecular-Beam Epitaxial Growth of GaN on Off-Axis SiC (0001). Jun Suda1,2, Yuki Nakano1 and Tsuenobu Kimoto1, 2Dept of Electronics Science and Engineering, Kyoto University, Kyoto, Japan; 2PRESTO, Japan Science and Technology Agency, Kawaguchi, Japan.

Integration of III-N materials with SiC is an interesting approach to realize high-performance wide-bandgap semiconductor devices. This approach can make it possible to utilize bandgap engineering in SiC-based devices. An AlN/SiC MISFET and a GaN/SiC HBT are two promising device structures. Because high-quality III-N homoepitaxial growth (necessary to fabricate the SiC active region) is not present established only on off-axis substrates, the III-N semiconductor must be grown on off-axis SiC. We have investigated growth of GaN and AlN on off-axis SiC substrates. Roughening of the surface after III-N growth is one of problems in this system. In this work, we report on growth of GaN on 4H-SiC (0001) S0–off toward the [11–20] direction, which is a standard substrate in SiC device fabrication. Before the growth of GaN, ex-situ high-temperature gas etching or homoepitaxial growth was carried out, resulting in a smooth SiC initial surface. However, the surface of the subsequently grown GaN layer has wavy features with peak-to-valley height of 30 nm. Since the direction of the undulations is parallel to the misorientation direction, this feature must originate from the substrate misorientation. From the results of these experiments, it was found that step bunching and large faceting along [01–10] and [10–10] directions occurred during the growth of GaN. Lowering the growth temperature suppresses large faceting, and vice versa. This result is the first to directly correlate the presence of stacking faults to the 364 nm emission from GaN. The nature of stacking faults has been analyzed using different diffraction conditions. Stacking faults on a-plane have been observed at sites of basal-plane stacking faults. The dynamics of jog formation will be presented. [1] B.-C. Chung and M. Gershenzon, J. Appl. Phys. 72, 651 (1992). [2] Y. T. Rebane, Y. G. Shreter, and M. Albrecht, Phys. Stat. Sol. A 164, 141 (1997).

Study on Surface Characteristics in Mg-doped GaN Light Emitting Diode Grown by MOCVD. Hyun Jung Lee, Baekyun Kim, Kyu Han Lee, Je Won Kim, Dong Joon Kim, Sun Woon Kim and Jeong Tak Oh; Samsung Electro-Mechanics, Suwon, Kyunggi-Do, South Korea.

Surface characterization in Mg-doped GaN epilayers is reported. Mg-doped GaN films, grown by metalorganic chemical vapor deposition (MOCVD), on the sapphire wafer are prepared in order to investigate surface morphology and dopant concentration. The Mg concentration in GaN films is measured by secondary ion-mass spectrometry and the surface morphology in a series of GaN layers is explored by atomic force microscopy. In GaN-based light emitting diodes (LEDs) and laser diodes (LDs), magnesium is usually used because of its high hole mobility and efficiency of hole capture. In Mg-doped GaN, the hole concentration in p-GaN can be limited in solubility in GaN [2]. To increase the hole concentration in p-GaN, the films are very heavily Mg-doped. The problem is that the mobility rapidly decreases with increasing Mg concentration in GaN due to compensation effects. At high Mg concentration, the mobility and the hole concentration in GaN is not measured. In this work, we report on growth of GaN layers on the surface of the films grown by MOCVD become rough [1]. Recently, it has been reported that Mg induce triangular pinhole-type defect, rectangular pinhole defect, and Mg-rich pyramidal defects to be pyramidal inversion defects in bulk GaN grown by MOCVD [5].

In-situ Monitoring of Growth Parameters during Epitaxial Growth of AlN. David Blais1, Vladimir Tassie2, David Weyburne1, Sheng-Qi Wang1, Mitchell Fait1, Jeffrey Anthi3, Nam Nguyen4, Mohammad Shams1, Chris Shasure2, and John R. Hennes2, 1Air Force Research Laboratory, Hanscom AFB, Massachusetts, 2Solid State Scientific Corporation, Hollis, New Hampshire, 3Epichem, Inc., Haverhill, Massachusetts.

The deposition rate of AlN by halide vapor transport epitaxy (HVTE) is monitored and controlled by in-situ measurement of the source gas composition. The source is an aluminum chloride–alumina additive with a known vapor pressure and decomposition temperature. In the chemical compound possesses relatively high vapor pressure of about

Abstract Withdrawn
3-5 Torr at working temperature range of 65–110°C and can be either in liquid or solid phase. A series of experiments using different carrier gases revealed that growth rate is highly dependent on the working gas material and temperature. The gas flow rate and growth temperature are major factors affecting the growth rate and the thickness of GaN/AIN superlattices. These results suggest that GaN/AIN superlattices can be grown with high efficiency.

**E8.39**

**Self-Organized Nano-Column GaN/AlN Superlattice Crystals Grown by RF-MBE.** Koji Yamano, Makoto Tada, Akihiko Kikuchi and Katsunori Kishino; Department of Electrical and Electronics Engineering, Sophia University, Chiyoda-ku, Tokyo, Japan.

GaN nanocolumns with GaN/AlN short period superlattice (SL) layers were successfully grown on (0001) sapphire substrate by RF-plasma assisted molecular beam epitaxy (RF-MBE). Clear satellite peaks from GaN/AlN SL layers were observed on X-ray diffraction spectra. The GaN/AlN SL layer showed intense room temperature photoluminescence (PL) emission at 430nm (blue) and 380nm (violet). These results suggest that the growth of high quality GaN/AlN nanocolumns. The GaN/AlN hetero-junction with a long conduction band offset (~2eV) is an attractive combination for various quantum effect devices such as ultraviolet interband transition (UV-IBT) modulators. These GaN/AlN nanocolumns with high-dislocation density was used to investigate the growth of GaN/AlN superlattice nanocolumns with two kinds of GaN/AlN SL nanocolumns with different SL structure (sample A and B) were grown by RF-MBE using rf-plasma excited nitrogen gas and elemental Ga and Al as sources. The GaN/AlN SL nanocolumns were grown as a sequence of AlN nucleation layer, GaN nano-column (300nm), GaN/AlN superlattice (100 periods) and GaN (300nm). The SEM observation, nanocolumns was grown with an average diameter, height and density of ~100nm, 900nm and 1~2×10^9 cm^-2 respectively. The layer thickness of GaN/AlN SL were evaluated from the satellite peaks of X-ray diffraction spectrum to be 8ML/12ML for the sample A and 10ML/15ML for sample B. Their c-axis was perpendicular to the substrate surface. Room temperature PL measurements were carried out before and after He-Ne laser (632 nm) irradiation. Strong emission peak was observed for both samples. The peak wavelength was 380nm for sample A and 450nm for sample B and the peak intensity was about 5~10 times stronger than that of conventional nanocolumns grown on non-dislocation free substrates with deposition density of 5.5×10^10 cm^-2 and thickness of 3.75μm. The calculated peak wavelength of AlN/GaN samples considering polarization effect are agreed well with experimental value. These results suggest that GaN/AlN SL nanocolumns are an attractive candidate for various quantum effect devices. This work was supported by a NEDO Industrial Technology Research Grant #02A28041d and Grant-in-Aid for Scientific Research (A) #14208057 from the Ministry of Education, Culture, Sports, and Technology.

**E8.40**

**Dislocation Reduction in GaN Epilayers by Maskless P-LE-P process.** Dong Jung Park1, Chang-Soo Seo2, Chang Min Yoon3, Chang Seung Hong3, Jung Hee Hong2, and Hyung Koon Cho1; 1Materials Science and Engineering, Korea Advanced Institute of Science and Engineering, Daedeon, South Korea; 2Metallurgical Engineering, Dong-A University, Busan, South Korea; 3Semiconductor Science and Technology, Chonbuk National University, Jeonju, South Korea.

GaN related alloys are of particular interest due to their ability to cover a wide spectral range that is not available from other III-V semiconductors. Up to now, the major problem of GaN growth has been the lack of a suitable substrate. A thick GaN layer has been successfully grown using nitrogen gas laser annealing technique in sapphire substrate without lattice mismatch (13%) and the difference of thermal coefficient. But the dislocation density in the GaN films grown on sapphire substrates has the range from 10^6 to 10^7/cm^2. Especially, most of threading dislocations propagate along the c-axis direction and destroy the active layers, which are believed to deteriorate the optical and transport properties. The representative techniques designed for the reduction of threading dislocation are epitaxial lateral overgrowth (ELoG) and Pendeo-epitaxial growth (PEG). The GaN/AlN superlattices were grown on 2-inch diameter sapphire wafers. However, it is an attractive combination for various quantum effect devices. This work was the lack of a suitable substrate. A thick GaN layers had been grown on c-plane sapphire substrates in spite of large extent than diffusion, as had been assumed at the outset. The dislocation density in the GaN films grown on GaN/AlN superlattice nanocolumns with GaN/AlN short period superlattice (SL) layer.

**E8.41**

**Time-Resolved Photoluminescence Studies of Eu³⁺ Centers in GaN.** J. Hong Ying Peng1, Henry O. Everitt1, Chang-Won Lee2, J. M. Zavada3, D. S. Lee4, and A. J. Steckl5; 1Department of Physics, Duke University, Durham, NC; 2US Army Research Office, Research Triangle Park, NC; 3Nanoelectronics Laboratory, University of Cincinnati, Cincinnati, OH.

In recent years, doping of GaN by various rare earth (RE) ions has attracted considerable attention in view of its unique luminescent properties including the well-defined narrow emission lines and their insensitivity to the host materials and temperature variation. However, some basic information about the incorporation, excitation, and emission properties of Eu³⁺ ions in the GaN host matrix are insufficient at present for optimization of GaN:Eu-based luminescent devices. In the present study, time-resolved photoluminescence (PL) and photoluminescence excitation (PLE) measurements were employed to study the carrier relaxation dynamics of the red luminescence (D⁰₋F₂) from GaN:Eu as a function of pump energy. Strong absorption occurs at pump energies above the GaN band edge, while a broad absorption tail below the band gap is observed instead. The corresponding assignments have been attempted within a wide range of energy. Strong emission peak was observed for both samples. The peak wavelength was 380nm for sample A and 450nm for sample B and the peak intensity was about 5~10 times stronger than that of conventional nanocolumns grown on non-dislocation free substrates with deposition density of 5.5×10^10 cm^-2 and thickness of 3.75μm. The calculated peak wavelength of AlN/GaN samples considering polarization effect are agreed well with experimental value. These results suggest that GaN/AlN SL nanocolumns are an attractive candidate for various quantum effect devices. The work was supported by a NEDO Industrial Technology Research Grant #02A28041d and Grant-in-Aid for Scientific Research (A) #14208057 from the Ministry of Education, Culture, Sports, and Technology.

**E8.42**

**Time-Resolved Analysis of Dislocation Density in AlGaN Grown on an AlN Template.** Noriyuki Kuwano1, M. Haraguchi2, A. Ishiga3, H. Miyake3, K. Hiramatsu3, and T. Shibata1; 1ASTEC, Kyushu University, Kasuga, Fukuoka, Japan; 2Dept Adv Sci for Electr Micro, Kyushu University, Kasuga, Fukuoka, Japan; 3Dept. Applied Electr, Mie University, Tsu, Mie, Japan; 4NGK Insulators Ltd, Nagoya, Aichi, Japan.

Growth of good quality AlGaN layers with high Al contents is essential for fabrication of light emitting/detecting devices for deep
Ferguson, fabricate functional quantum gates of semiconductor quantum dots. Studies of nitrides aiming at evaluation of phase coherence time down to spin decoherence and strong spin-spin coupling are required to successfully on an AIN template, but that in the case of AIGaN layers, the dependence of the room temperature ferromagnetic properties of GaN:Mn/GaN:Mg double heterostructures (DHS) on the Fermi level position in the crystal is not understood. Several GaN:Mn/GaN:Mg DHS are grown by metal organic chemical vapor deposition on sapphire. It is shown that initially paramagnetic films can be rendered ferromagnetic by facilitating carrier transfer through the GaN:Mn/GaN:Mg interface, so it is deduced that ferromagnetism depends on the thickness of the GaN:Mn and GaN:Mg layers. The carrier transfer process essentially changes the Fermi level position in the crystal. By choosing the right thicknesses for GaN:Mn and GaN:Mg an optimum room temperature ferromagnetism is grown. An identical structure, with the exception of insertion of an AIGaN barrier in order to obstruct the carrier transfer at the interface, results in paramagnetic films for AIGaN barriers thicker than 25nm. These results are explained based on the occupancy of the 3d-Mn impurity band, and indicate that carrier inhibition is the possible mechanism for the ferromagnetism observed in the MOCVD grown GaN:Mn material system. This is the first evidence that this material system responds to electronic perturbations, hence ferromagnetism observed is not due to secondary phases or spin glass behavior.

9:15 AM E9.4
Synthesis and Properties of GaxMn1-xN films. Rong Zhang, Physics, Nanjing University, Nanjing, China.
Jiangsu Provincial Key Laboratory of Photonic and Electronic Materials and Science and Technology, and Department of Physics, Nanjing University, Nanjing 210093, People’s Republic of China. Since the prediction that GaxMn1-xN has a high-temperature room temperature on the basis of a mean field model by Dietl et al, GaxMn1-xN has attracted much attention as a diluted magnetic semiconductor (DMS) for developing spin-based electronic and optoelectronic devices. In this paper, MOCVD-grown GaN films on HVPE-grown GaN substrate were prepared using HVPE technique. From the XRD, XPS, AFM, Raman and VSM measurements were carried out to investigate structural and magnetic properties of these films. Mn-doped GaN film was grown by a horizontal HVPE (Heteroepitaxial Vapor-Phase Epitaxy) system with two parallel metal source boats. One boat is for metallic Ga source and the other one is for metallic Mn doping. HCl gas was supplied to react at 850°C with liquid Ga and Mn, respectively, while N2 gas was used as carrier gas. NiS was used as the source. A 1um-thick HVPE-GaN layer was used as substrate for epitaxy of Mn-doped GaN films. The growth temperature is 1050°C. A 4mm-thick layer was grown on HVPE-GaN substrate after 15 minutes growth. X-ray diffraction and x-ray photoelectron spectroscopy measurements indicate that GaxMn1-xN films have been synthesized with x up to 0.16. The lattice constant of the epilayer decreases with the Mn composition. AFM characterization indicates that Rms (root-mean-square) roughness is in the nanometer range. Raman scattering measurements indicate that the phonon frequencies of E2 (low), E2 (high), A1(TO) and A1(LO) modes of HCl-grown GaN are 144, 567, 533, and 734 cm^{-1}, respectively. We measured the magnetic properties of the Mn-doped samples, there are some obvious differences compared with the undoped GaN sample. First, two broad bands come forth centered at 302 cm^{-1} and 674 cm^{-1}. The first band is due to the Mn-doped GaN sample, while the second band is due to the Mn-doped GaN sample. The second band is due to Mn-doped GaN sample. Second, a new peak arises at wave numbers of 589 cm^{-1}. We deem that the 589 cm^{-1} peak is attributed to local vibrations of Mn ions in GaxMn1-xN as a result of substitution of Mn into Ga sites. Third, the A1(LO) peak of Mn-doped sample is strongly asymmetric and show a considerable redshift of 8 cm^{-1}. This redshift can be explained by the variety of charge carrier concentration. VSM measurements show that the magnetic properties are measured at room temperature, indicating that the films are ferromagnetic at room temperature. M-T measurements give evidence that the films are ferromagnetic at room temperature. For the Mn-doped GaN films, the magnetic properties are measured at room temperature. The Mn-doped GaN films, the magnetic properties are measured at room temperature. The magnetic properties of Mn-doped GaN films will be discussed.

9:30 AM E9.5
Import of Magnetic Incorporation on the Structural and Magnetic Properties of MOCVD-Grown GaN. Z. N. Ge, H. Shen, H. Zhang, R. Zhang, J. Tian, and Z. L. Xie. School of Materials Science and Engineering, Georgia Institute of Technology, Atlanta, Georgia; School of Chemistry and Biochemistry, Georgia Institute of Technology, Atlanta, Georgia.
Technology, Atlanta, Georgia; 4Department of Physics and Astronomy, Georgia State University, Atlanta, Georgia; 5Institut fuer Festkoerperphysik, Technische Universitaet Berlin, Berlin, Germany.

We report on the metal-organic vapor phase epitaxy (MOVCD) growth and the impact of the Mn incorporation on the structural, optical and magnetic properties of the GaN:Mn epilayers. Mn films of varying thickness and manganese doping levels were grown by introducing Bis-cyclopentadienyl manganese (Cp2Mn) into a chemical laser head reactor during the GaN growth. Crystalline quality and phase purity are determined by x-ray diffraction indicating that no macroscopic second phases are formed. In addition, no shift in the lattice parameter was observed. AFM revealed a mean surface roughness of 3.78 Å, which is close to that from the as-grown template layers [300 Å uniform Mn concentration]. Secondary ion mass spectroscopy (SIMS) confirmed by X-ray photoelectron spectroscopy. An annealing step at 800 °C for 4 minutes in nitrogen atmosphere was applied to some of the samples to reduce compensating defects. This was confirmed by photoluminescence investigations. A broad emission band ranging from 2.7 eV to 3.1 eV were observed in the as-grown samples indicating that the MOVCD-grown GaMnN epilayers.

Most of these defects were removed by the annealing procedure. Electron spin resonance (ESR) was applied to study the incorporation and the electronic structure of the manganese ions. Despite the small volume of the GaMnN epilayers, valuable results were obtained. For the annealed samples, resonances corresponding to the hyperfine structure were observed. These observed resonance patterns are well described by the spin Hamiltonian for isolated 55Mn2+ centers with electronic spin S=5/2 and nuclear spin I=5/2. The Mn3+ state is not ferromagnetic, special preparation of the epilayers (shift of the Fermi level towards the valence band) is required. A clear distinction between the possible Mn ion states is observed using optical spectroscopy (e.g., photoluminescence) and electron spin resonance (ESR). Spectroscopic investigations on the structural and optical properties of Mn-doped GaN-MnAs and local fluctuations of the Fermi level facilitating the formation of Mn3+ ions are considered to explain the observed ferromagnetism. The latter is supported by the observation of an absorption band around 1.8 eV that is tentatively assigned to a Mn2+ contribution of theoretical ideas to our understanding of excitation transition probability for favourable sites. This talk summarises evidence obtained to date for the existence of site multiplicity of RE ions in III-N hosts. Firstly, we review studies which aim to reveal the lattice location of host ions in semiconductors and some details of the local environment. These are compared with the results of spectroscopic studies, which are characteristic of RE in optically active sites. Finally, the concept of 'RE-related defects' and the contribution of theoretical ideas to our understanding of excitation mechanisms are critically examined. Although a complete prescriptive materials science of III-N:RE defects is some way off, preliminary results are encouraging. [1] A. J. Steckl et al., Materials Science and Engineering B 81, 48 (2001) [2] I. G. Garte and A. J. Steckl, IEEE Transactions on Electron Devices 49, p 48 (2002).

9:45 AM E9.5

Optical and Structural Investigations on Mn Ion States in MOVCD-grown GaN-MnN, M. Martin Strassburg,1,2,3,4 Jayantha Sensurinante1, Nikolaus Dietz1, Matthew H. Kane2, Ali Asghar2, Adam M. Payne2, Ian T. Ferguson3, Christopher R. Summers4, Ute Haboeck5, Axel Hoffmann5, Dmitry Azamat5 and Wolfgang Gehlhoff6,1

1School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, Georgia; 2School of Materials Science and Engineering, Georgia Institute of Technology, Atlanta, Georgia; 3Institut fuer Festkoerperphysik, Technische Universitaet Berlin, Berlin, Germany.

Recent theoretical predictions suggesting ferromagnetism of diluted magnetic semiconductors with Curie temperatures above room temperature have increased efforts on transition metal (TM) doped wide bandgap materials, such as Ga1-xMnxN. Since the Mn24+ state is not ferromagnetic, special preparation of the epilayers (shift of the Fermi level towards the valence band) is required. A clear distinction between the possible Mn ion states is observed using optical spectroscopy (e.g., photoluminescence) and electron spin resonance (ESR). Spectroscopic investigations on the structural and optical properties of Mn-doped GaN-MnAs and local fluctuations of the Fermi level facilitating the formation of Mn3+ ions are considered to explain the observed ferromagnetism. The latter is supported by the observation of an absorption band around 1.8 eV that is tentatively assigned to a Mn2+ contribution of theoretical ideas to our understanding of excitation transition probability for favourable sites. This talk summarises evidence obtained to date for the existence of site multiplicity of RE ions in III-N hosts. Firstly, we review studies which aim to reveal the lattice location of host ions in semiconductors and some details of the local environment. These are compared with the results of spectroscopic studies, which are characteristic of RE in optically active sites. Finally, the concept of 'RE-related defects' and the contribution of theoretical ideas to our understanding of excitation mechanisms are critically examined. Although a complete prescriptive materials science of III-N:RE defects is some way off, preliminary results are encouraging. [1] A. J. Steckl et al., Materials Science and Engineering B 81, 48 (2001) [2] I. G. Garte and A. J. Steckl, IEEE Transactions on Electron Devices 49, p 48 (2002).
Aqua marine Luminescence Band in Undoped GaN
Michael A. Reszhakow,,1 Lei He,2 Richard J. Molnar,3 S. S. Park,4 K. Y. Lee,5 and Hidaj Morkoc,6,7 1Physics, Virginia Commonwealth University, Richmond, Virginia; 2Electrical Engineering, Virginia Commonwealth University, Richmond, Virginia; 3Lincoln Laboratory, Massachusetts Institute of Technology, Lexington, Massachusetts; 4SAIT, Suwon, South Korea.

We report a new defect-related photoluminescence (PL) band in undoped GaN. These bands were grown by metal-organic vapor phase epitaxy. Our results show that GaN layers grown by metal-organic vapor phase epitaxy have a broad PL band with a maximum at 2.55–2.56 eV at low temperatures. With increasing temperature, the broad band layer, and its maximum gradually shifts to higher energies with a total shift of 80–90 meV up to room temperature. The yellow luminescence band could be detected in these samples only as a shoulder to the broad PL band at low excitation intensities. Although the shape and the peak position of the PL band are close to the characteristics of the green luminescence band in a freestanding GaN template, we distinguish these two bands for their markedly different behavior with temperature and excitation intensity.

SESSION E10: Lasers and Light-Emitting Diodes II
Chairs: Kevin P. O’Donnell and ShigetaTokii-Tomiya
Thursday, December 2, 2004
Buck Bay C (Sheraton)

A new and expanding area of research is the exploration of nitride-based materials and device structures for electroluminescence at wavelengths shorter than 300 nm. Interest in this wavelength range is motivated by the large number of applications that would benefit from compact, robust, wavelength-tunable, high-power sources. These applications include fluorescence-based biological agent detection, water purification, sterilization and decontamination, nonline-of-sight communications, and thin film curing. While deep-UV (380–400 nm) light emitting diodes (LEDs) employ InGaN quantum well structures with GaN barriers, reaching deep-UV wavelengths requires AlGaN alloys with aluminum concentrations of 50% and higher. These wide bandgap LEDs suffer from a number of materials issues which can dramatically reduce LED performance, including high dopant ionization energies and tendency for dopant compensation, high densities of threading dislocations (typically > 10^10 cm^-2), and large internal fields due to spontaneous polarization and piezoelectric effects. In this presentation, we will discuss the material and device challenges for achieving high performance devices and will present recent advances in AlGaN-based deep-UV LEDs. We will present data on LEDs that are grown by metalorganic vapor-phase epitaxy and employ flip-chip device geometries. These devices have yielded greater than 1 mW output powers at 276 nm and greater than 2 mW at 297 nm under DC current operation. Critical device performance data that will be presented include temperature-dependent electrical and optical properties, device lifetimes and degradation characteristics, and an evaluation of the origins of deep level emission in the electroluminescence spectrum. Electroluminescence at wavelengths shorter than 297 nm will be obtained by post-irradiation-produced Ga Frenkel pairs and by post-irradiation-produced Frenkel pairs near room temperature. The subsequent disappearance of detectable H-related absorption can be explained by the trapping of the H in the N vacancy or its complex with Mg; the local modes predicted for these complexes are not expected to be observable in GaN films on sapphire.


Using X-ray photoemission spectroscopy (XPS) we have measured the band offsets of ZnO-GaN heterojunctions for both N-face and Ga-face GaN. ZnO epilayers were prepared by MBE on unintentionally doped GaN films grown on sapphire substrates. The N-face GaN layer was doped by growth in organometallic mixtures containing N species while an AlN buffer layer was employed for the Ga-face GaN. The ZnO films are sufficiently thin (2 nm) to allow simultaneous XPS detection of the core levels from the ZnO film (N 1s, O 1s) and the GaN substrate (Ga 3d, N 1s). The valence band heterojunction band offset was deduced from the difference in the core level positions where the valence band of each material was determined from prior XPS and UPS measurements of clean GaN layers and bulk ZnO. We found the ZnO valence band to be positioned below the GaN valence band at 1.85 ± 0.1 and 1.05 ± 0.1 eV for the Ga-face and N-face heterojunctions, respectively. Assuming $E_g(GaN) = 3.4$ and $E_g(ZnO) = 3.3$ eV, the Ga- and N-face conduction band offset is 1.93 and 1.15 eV, respectively. Two methods used for each configuration is deduced based on the deviation from the electron affinity model, and the band offsets are analyzed in terms of the interface banding.

The interaction of defects and hydrogen in proton-irradiated GaN(Mg,H). Carleton H. Seager1 and Sam M. Myers2 1Materials Science & Engineering, North Carolina State University, Raleigh, North Carolina; 2Materials Science & Engineering, North Carolina State University, Raleigh, North Carolina.

The interaction of defects and hydrogen in p-type GaN was investigated using MeV proton irradiation in conjunction with infrared absorption spectroscopy, nuclear-reaction analysis (NRA) of the hydrogen isotope distribution, and photoluminescence. During post-irradiation annealing the system was observed to undergo a series of changes which were interpreted in terms of reactions among the four intrinsic point defects and hydrogen. The Mg-doped GaN contained either both Mg-N and Mg-H or a single source of hydrogen from gas-phase charging. It was first irradiated at room temperature to produce Ga and N Frenkel pairs at densities comparable to the Mg concentration, and then subjected to a sequence of isochronal anneals extending from 300 to 1000°C. In the temperature range 300–500°C, the local vibrational modes identified with H(D) bonded to Mg acceptors disappear and are replaced with new modes located 12 cm^-1 higher in energy. Roughly concurrent with this change, a new green luminescence band grows at 520 nm. At annealing temperatures above 500°C, the new vibrational mode begins to disappear, and the original signature of MgH(D) is partially restored. After annealing at 900°C the green luminescence is reduced by a large multiple, and observable H(D)-related absorptions vanish, despite the fact that NRA measurements indicate that roughly half of the hydrogen remains in the GaN. Anneals at 900°C complete the thermal release of hydrogen. We propose a model wherein the irradiation-produced Ga Frenkel pairs are annihilated near room temperature, leaving the N interstitial and N vacancy to influence the electron temperature behavior. The new, slightly weaker absorption is ascribed to the migration of a point defect, probably the N interstitial, into the vicinity of the Mg-H complex. Subsequent disappearance of detectable H-related absorption can be explained by the trapping of the H in the N vacancy or its complex with Mg; the local modes predicted for these complexes are not expected to be observable in GaN films on sapphire.

Homo- and Heteroepitaxy for GaN-Based Laser Diodes. S. Figge, T. Boettcher, J. Dennenmark, S. Einfeldt, C. Roder and D. Hommel 1Institute of Solid State Physics, University of Bremen, Bremen, Germany.

Epitaxy of GaN-based laser diodes (LDs) is nowadays normally carried out on hetero substrates like sapphire or silicon carbide. The large lattice mismatch of the GaN to these substrates requires techniques like laterally enhanced overgrowth to reduce the defect density of the material to an order of 10^6 1/cm². Sapphire has in comparison to GaN a warmer thermal conductivity and therefore the heat accumulation in the device derogates the performance of heteroepitaxially grown devices to a larger extent. Homoeptaxy of GaN based laser diodes has a lot of advantages, but still no bulk growth method is capable to gain crystals in adequate size for wafer production. This bottleneck can be circumvented by the growth of thick GaN layers on sapphire substrates utilizing hydride vapor phase epitaxy (HVPE) and a subsequent separation of the GaN layers from the substrate. A problem of these thick GaN layers is the large difference in thermal expansion coefficient with respect to the sapphire substrates which can lead to cracking of the GaN layer during cooldown in the HVPE process. In this talk we will give a survey of the current activities in Europe concerning nitride based LDs and we will address the different problems which are connected with both hetero- and homoeptaxy of laser diodes. Laser diodes grown by metal organic vapor phase epitaxy on different substrates have been processed both as gain guided as well as ridge waveguide structures.
The influence of process parameters during chemical assisted ion beam etching and subsequent crystallographic wet etching on the quality of III-nitride layers will be discussed. Thermal expansion coefficient measured from thermoreflection experiments on GaN substrates reveal an improved performance of devices grown on GaN substrates. Calculations on the thermal resistance show a three times better heat dissipation from the LED chip of devices grown on GaN substrates. Additionally the thermal expansion coefficient of GaN has been determined by highly resolved x-ray diffraction within a temperature range from 20 K up to 1000 K. With the help of a Debye model we used an analytical formula to describe the temperature dependent expansion coefficient over the whole temperature range. These data have been applied to calculations of thermally introduced stress of thick GaN layers and are linked with experimental data like wafer curvature and fracture toughness of HVPE grown layer on sapphire.

2:30 PM E10.5
Development of LED Structures for General Illumination. Jing Li1, 2', Ali Asghar3, Dhairya Mehta3, My Tran3, Hun Kang3, Ian T. Ferguson1, Mustafa Alevli1, Jayantha Jayasundera1, Christoph Hums2, Martin Strassburg2, Nikolaius Dietz2 and Axel Hoffmann2.

A series of GaN/GaN multi-quantum well light emitting diode (LED) structures have been grown and fabricated into diodes. The emission characteristics were investigated by photoluminescence (PL) and electroluminescence (EL) and the results compared. The comparison of EL to PL results gives insight into the emission mechanisms as well as allows evaluation of PL as a characterization method for LEDs. Scratch diodes and fabricated devices were compared with EL measurements to determine if scratch diodes can be used as an analytical tool. Using scratch diodes and fabrication of devices, bright emission attributed to the recombination of electron hole pairs in the InGaN/GaN MQW was observed in the blue spectral range. The emission peak ranged from 450 to 480 nm. Emission wavelengths for the quantum well were controlled by changing growth conditions such as temperature and well width (growth time). The sensitivity of quantum well emission to changing growth conditions was evaluated. Fabricated diodes were prepared using a standard 5mm die process. Some the diodes exhibited unusual PL behavior.

2:45 PM E10.6
Thermal Analysis of Multi-Quantum Well LEDs in InGaN/GaN/Sapphire Structure Using Nematic Liquid Crystal Thermography. Jeong Park1, Chin C. Lee3 and MooWhan Shin2.

The conversion efficiency of lighting LEDs is important device parameter and the quantum efficiency increases with decreasing temperature (TJ) increases. Based on device physics, the temperature that directly affects the efficiency is the junction temperature (TJ) rather than TC because TJ is the temperature of the active region where carrier injection and photon emission occurs. However, the relationship between efficiency and TJ is not available because TJ is unknown during LED operation. In this design, we perform a series of PHIT experiments on InGaN/GaN MQW LED structures. The junction temperature is revealed when comparing the PL efficiency with measured values at different temperatures. The relationship between efficiency and TJ is obtained from the thermal management technique using nematic liquid crystal thermography. This technique can provide accurate temperature within +/-1 C. However, in applying this technique to LEDs, great difficulty exists. The LED light during operation would easily overwhelm the illumination light from the external optical microscope used in the setup. Thus, the microscope light reflected from the LED chip surface that carries the temperature information is totally lost. To overcome the difficulty, a new configuration is established where high power laser diode of 473 nm wavelength is used as the new illumination source to sense the temperature. Color filter is inserted in the optical path to attenuate the overwhelming LED light. The use of high power laser beam thus greatly enhances the contrast of the thermal image on the surface of LED chip. Since InGaN/sapphire is transparent at 780nm, the laser beam does not heat up the LEDs. For the LEDs studied, the conversion efficiency decreases by 70% when the junction temperature increases between 25C to 107C. The thermal resistance is measured to be 17C/Watt. The peak temperature is found near p-contact, agreeing with fact that this region has the highest current density. With the relation between conversion efficiency and junction temperature available, the device physicists and engineers can establish a physical model and find ways to modify the device structure to reduce the temperature dependence of conversion efficiency on junction temperature. In passing, we also measured the current versus voltage, and found the diode can be modified to achieve the desired performance.

3:00 PM E10.5
Nitrile LEDs on 6‘ Si substrates. Jing Li1, J.Y. Lin2 and Hongxing Jiang2.

The growth of III-nitrides on Si substrates presents a unique opportunity for the fabrication of blue/green LEDs on substrates with large area, low cost, and high electrical and thermal conductivity.

3:30 PM E10.6

There are many kinds of nitrile-based devices ever developed, such as blue, green and near-UV LEDs, violet LD, HEMT and so on. However, all the nitrile layers used in commercial devices are grown on lattice-mismatched c-face sapphire or Si substrates, and their growth direction is along with c-axis. The lattice mismatch between nitride layers and such substrates leads to the generation of threading dislocations, so that the special techniques for the reduction of the dislocations are required. Furthermore, the internal polarization normal to the surface certainly occurs because of the c-axis-oriented growth direction. This type of polarization is perpendicular to quantum-wells or two-dimensional electron gas, and temperature dependent effect on nitrile-based devices, so that it often causes undesirable effect on the device performance. One of the aims in this work is to solve the above mentioned substrate issues, i.e. development of novel substrate materials which are potentially low cost and suitable for UV optoelectronic devices, and establishment of non c-axis nitrile growth with particularly oriented substrate. The unique substrates including ZrB2, (30-38) SiC and R-faceted sapphire are evaluated for the application to many light-emitting diode devices. The ZrB2 has a hexagonal AlB2 atomic arrangement, and perfectly lattice-matched to Al0.49Ga0.51N. With the other excellent physical properties such as high electrical and thermal conductivity, this substrate material is promising for the application to nitride-based LEDs. The (30-38) SiC and R-faceted sapphire make overgrown nitride layers possible to have non c-axis orientation, so that the elimination or reduction of internal polarization in the nitride-based heterostructures could be realized. Using such materials as substrates,
we investigated crystal growth of nitride layers by metalorganic vapor phase epitaxy. All the GaN layers grown on these substrates had specular surface, and exhibited good homogeneity over larger areas than the usual FWHMs of XRD for them to be broader than that of c-faceted GaN on a sapphire substrate. The fabrication of violet LEDs on these substrates were also carried out, while the growth technique on the (30-38) 4H-SiC and c-faceted sapphire is under early stage of the development. Single peak wavelengths ranging form 405 to 425 nm were observed for all LEDs, however, the emission efficiency of LEDs except that on the ZrB$_2$ were still low. As for the LEDs on the (30-38) 4H-SiC and c-faceted sapphire, a blue shift in the current was confirmed, which may be an evidence of the reduction of internal polarization. With the further improvement of crystalline quality, these new substrate materials are promising for high-efficiency nitride-based LEDs.

E10.7


InGaN/GaN multiple-quantum-well light-emitting diodes (LEDs) with peak emission at 405 nm were grown on bulk GaN and sapphire substrates using MOCVD. The bulk and surface defect densities in the homoepitaxial LED were substantially reduced compared to the device on sapphire, leading to greatly improved electrical characteristics. The tunneling current, which was found to be dominant in the LED on sapphire over a wide range of applied bias, was remarkably suppressed in the homoepitaxial LED. Temperature-dependent measurements showed that tunnelling-recombination current dominated at intermediate forward bias, and reverse-bias current was originated from carrier generation and tunneling associated with deep-level traps. Nanoscale surface characterization, conductive-electric force microscopy (C-AFM) and scanning Kelvin probe microscopy (SKPM) revealed highly localized surface potential decrease and leakage current at V-defects in the LED structure on sapphire, indicating that the associated screw and mixed dislocations were electrically active and behaved as leakage current pathways connected across the p-n junction. The homoepitaxial LED exhibited superior optical characteristics in all injection regimes, which was attributed to reduced nonradiative recombination centers at low injection levels, and the combined effect of better material quality, heat dissipation and current spreading at high pump currents. Compared to conventional lateral LEDs on sapphire, the vertically-structured device on GaN had a reduced series resistance of 7 ohm, and greatly improved power conversion efficiencies (28% higher at 500 mA, or 700 A/cm$^2$). The vertical LED was subjected to stress test at 400 mA and showed minimal degradation of optical power, whereas the same stress resulted in the destruction of the lateral LED on sapphire due to increased current crowding and self-heating. Combined with advanced packaging, the homoepitaxial LED is very promising for developing high brightness and cost-efficient solid-state lighting sources.

4:15 PM E10.6

Reliability and Operation Lifetime Studies of sub-280 nm Ultraviolet Emitters on Sapphire Substrates, Ashag Chitnis, Maxim Shatalov, Wu, Salih Suyig, Wenhong Sun, Vinod Advarahan and M. Asif Khan; Electrical Engineering, Univ. of South Carolina, Columbia, South Carolina.

High efficiency III-Nitride based visible light emitting diodes (LEDs) are now available commercially for numerous applications such as displays, optical sensing, signal sources, etc. Currently, there is considerable research effort focused towards developing sub-300 nm emission ($\lambda < 300$ nm) high power deep ultraviolet (UV) emitters to be used in biochemical detection and air/water purification etc. Several groups including ours have reported AlGaN-based sub-280 nm deep UV emitters on sapphire substrates. Recently, we have improved the reliability of these ultraviolet emitters by achieving a new quantum well design and improved contacts along with flip-chip packaging. This has yielded continuous-wave (cw) powers of 0.46 mW at a saturation current of 100 mA for a single 100$\mu$m x 100$\mu$m device. For an array of 40 $\mu$m x 100 $\mu$m packaged devices, record cw power of 1.13 mW was measured at bias current of 450 mA. Inspite of these impressive power numbers the efficiency of these sub-300 nm emission LEDs is still low. Thus for high power levels the devices need to be designed for high-current applications (approaching the hole lifetime) for the second phase, suggesting use of a uniformly distributed luminance center. In contrast, the 575 nm peak did not show a clear two-step response, implying a complex temperature-dependence of the mobility. These results suggest that hole temperature in high-Al-content AlGaN is completely dominated by imperfection transport, with transport possibly occurring by percolation through a high-density network of defects. Sandia is a multimodal program laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the US Department of Energy under contract DE-AC04-94AL85000.

4:45 PM E10.10

High Power 340 nm UV-LEDs Grown by Plasma Assisted Molecular Beam Epitaxy (PAMBE), Jasper S. Cabana,1 Christos Thomaidis,3 Anirban Bhattacharya2, Theodore D. Mouzakos,3 and Charles Collins2; 1Electrical and Computer Engineering, Boston University, Boston, Massachusetts; 2U.S. Army Research Laboratory, Adelphi, Maryland.

The development of ultraviolet emitters has various potential applications in low cost solid-state white lighting, portable biological and chemical detection/analysis systems, medical diagnostic and therapeutic systems, and ultra-sensitive high density optical data storage. In this paper, we report on the growth by MBE and fabrication of high power UV-LEDs emitting at 340 nm. The devices were grown on (0001) sapphire substrate via plasma assisted molecular beam epitaxy (PAMBE) and the active region of the device consists of GaN/AlGaN.
multiple-quantum wells (MQWs). A number of device design, fabrication and packaging issues were addressed in order improve the device efficiency. Laser diodes were mesa etched for different geometries were fabricated using conventional optical lithography and were designed for backside light extraction. The LED design took advantage of peripheral n-contact to minimize current crowding. Finger-type mesa design was also incorporated to sufficiently increase current spreading brought about by the resistive nature of the p-type GaN contact layer. The LEDs were flip-chip bonded onto single devices or arrays of twenty devices, which can be lighted up simultaneously onto a Si substrate for better heat sinking. Bare die devices were characterized under pulsed and continuous wave operation. Initial data gathered showed a differential on-series resistance as low as 15 ohms with electroluminescence (EL) spectra full-width at half-maximum (FWHM) of 17 nm. Continuous mode operation (DC) of the devices showed output powers as high as 0.7 mW at 200 mA injection current, which is the highest reported that we know for MBE-grown UV-LEDs. The peak wavelength varies with DC device current from 3.5 nm to 4.1 nm, which is attributed to device heating. Packing of the devices through flip-chip bonding process is expected to improve the thermal management of the device and thus the overall optical output to powers greater than 1 mW.

SESSION E11: Poster Session
Chairs: Detlef Hommel and Martin Kuball
Thursday, December, 2004
8:00 PM
Exhibition Hall D (Hynes)


Ongoing efforts of growing large AIN single crystals at NCSU using an induction heated high temperature reactor are based on (1) engineered expansion of single crystalline grains with increasing boule length, as well as (2) the development of a growth process that enables seeded growth on AIN surfaces previously exposed to air. The growth process is based on physical vapor transport (PVT), where AIN powder is sublimed in a high purity nitrogen atmosphere. The growth temperature was typically in the range of 2100 to 2150 °C while the reactor pressure was kept between 200 – 500 Torr. First, high quality seeds were prepared by grain expansion starting with a self-nucleated layer of polycrystalline material. Grains were found to expand from sub-millimeter to cm-size in 25 mm long boules. The growth was interrupted several times in order to refill the AIN powder source and the growth surface was subject to surface preparation to facilitate epitaxial re-growth. Details on grain expansion and its dependence on process parameters will be discussed. XRD rocking curve analysis, X-mode and defect-selective etching indicate that the grown crystals have a high crystalline quality and low extended defects density.


Highly doped p-type GaN using Magnesium was grown for incorporation as a tunnel junction into dual wavelength light emitting diodes. These dual emitters will be used for phosphor pumped devices. Highly doped p-type material is necessary for creating efficient tunnel junctions that act as buried current spreading layers. It is also desired to provide high quality contacts to p-type GaN. Molar flow ratios and growth temperature were varied to achieve maximum doping concentrations. A range of post growth annealing conditions was used to activate incorporated Magnesium. Hall and Secondary Ion Mass Spectrometry (SIMS) were used to measure carrier concentration and Magnesium incorporation, respectively. Hall measurements also provide other information about the material such as resistivity and mobility which are useful in determining the electrical quality of the material. The maximum carrier concentration achieved was 1×10^20 cm^-3 and employed a low growth temperature of less than 1000 °C; high molar flow ratios. After growth the samples was annealed at 500 °C for 30 minutes, which proved more effective than a shorter anneal at higher temperature. In addition, annealing in ambient seems to give an improvement in Magnesium activation. Tunnel junctions with highly doped p-type GaN Current-Voltage measurements were taken on these devices to evaluate the effectiveness of the devices.

E11.3 Study on the Sublimation Growth of AIN Bulk Crystals. Hiroshi Iijima, Naoki Hata, Satoshi Kameya, Hisashi Amano*, Isamu Akasaki†, Takashi Tachibana‡ and Tadashi Nozu§; 1Materials Science and Engineering (21st Century COE Nanofactory), Meijo University, Nagoya, Japan; 2Ceramic Operation, Ibiden Company Ltd., Ogaki, Japan.

The lack of suitable substrate materials that are both lattice and thermally matched to the group-III nitride semiconductors presents a serious challenge to realizing high quality light emitting diodes in the fields of opto-electronics and electronics. Successful growth of high quality AIN single crystals will solve this problem to a great extent. We have made an attempt to study the growth kinetics of AIN single crystals by sublimation (seeded and seedless spontaneous nucleation growth) with the ultimate aim of fabricating substrate quality crystals. A water cooled sublimation system capable of operation under high vacuum levels is employed in this study. The system is designed to operate at 760 Torr. The reactor pressure was boosted to 5 x 10^-7 Torr and kept at this vacuum condition for more than 8 hours before performing crystal growth in a high purity nitrogen ambient. Seeded growth is performed on (001) oriented 6H-SiC substrates. The single crystalline AIN results in the temperature range of 1976-2100°C when the source-substrate distance and the temperature gradient are kept at 6 mm and 1.8°C/mm, respectively. The grown crystals look transparent and almost colorless. The maximum size of the crystals grown by SCD seeded method are 9×6×0.3 mm^3. The best crystal resulted exhibits an XRD omega rocking curve FWHM of 4.81 arcminutes. AIN growth is found to start off with the formation of hexagonal islands. Later, the hexagonal islands coalesce and form the complete crystal. AIN grown on Si-SiC and C-SiC show different growth behaviors. In the microscopic analysis, it is found that the growth on C-SiC is more of an agglomeration of defects. No clear hexagonal patterns are observed. In addition, many micro and nano trenches get generated, possibly due to poor coalescence of islands. The AIN layers grown on C-SiC is easier to peel off when compared with the layers grown on Si-C. The growth rate and the XRD rocking curve FWHM are different for the crystals grown under the same conditions. The spontaneously nucleated crystals exhibit a unique structure with (10 0) and (1 0 0) as the dominant faces although growth is found to have propagated faster along the c-direction. The crystals are thin (thickness range 7 - 10 μm) and transparent. There is no clear evidence of the crucible 40 mm away from the source indicating that they are more out of convective or buoyancy driven transport rather than the mass transport. The impurity incorporation is found to be less in the spontaneously nucleated crystals. In addition, there is no problem of cracking in this type of crystals unlike the crystals formed by seeded growth. Acknowledgement: This research is partially supported by the MEXT (#S200601) and Almaski Research Center, Nagoya University, Nagoya, Japan.

E11.4 In-situ Measurements of the Critical Thickness for Strain Relaxation in AlGaN/GaN Heterostructures. Stephen R. Lee1, Dan Koleske1, Karen Cross1, Jerry Floro1, Karen Waldrip1, Adam Wise2 and Subhash Mahajan1; 1Sandia National Laboratories, Albuquerque, New Mexico; 2Department of Chemical and Materials Engineering, Arizona State University, Tempe, Arizona.

Pseudomorphic AlGaN alloys grown on (0001) GaN have tensile in-plane misfit strains ranging from 0 to 2.38%. The elastic energy generated by these misfit strains drives fracture, plastic deformation, and surface instabilities during epitaxial growth of these materials – resulting defects degrade the performance of optoelectronic devices made of these alloys. Consequently, the critical thickness where fracture and dislocation glide become possible in AlGaN/GaN places important limits on the design of device heterostructures. In this presentation, we will report in-situ wafer-curvature measurements of the critical thickness for strain relaxation in Al(x)Ga(1-x)N/GaN epitaxial thin films with composition ranging from Al0.05Ga0.95 to x = 1. We will also report atomic-force microscopy (AFM) studies of the surface morphology exhibited by partially relaxed AlGaN samples. Comparison of the wafer-curvature measurements to critical-thickness models for both brittle fracture and dislocation glide suggests that the onset of strain relaxation occurs by surface fracture for all compositions. AFM of Al(x)Ga(1-x)N layers grown to the critical thickness (11 nm) shows terminated surface-fracture channels in full support of this interpretation. AFM images show how the change in the overall surface morphology of very thin AlGaN layers as composition and ammonia flow are varied. As we will discuss, these varying surface morphologies produce dissimilar inhomogeneous states in the underlying thin films, which influence dislocation glide, a process not previously observed in situ. Taken as a whole, our results show that strain relaxation in AlGaN alloys proceeds through a complex interplay involving fracture, surface morphology, and dislocation glide. Sandia is a multiprogram laboratory operated by Sandia.

Ell.2 Chairs: Detlef Hommel and Martin Kuball
SESSION Ell: Poster Session
Exhibition Hall D (Hynes)

Ell.3 In-situ Measurements of the Critical Thickness for Strain Relaxation in AlGaN/GaN Heterostructures. Stephen R. Lee1, Dan Koleske1, Karen Cross1, Jerry Floro1, Karen Waldrip1, Adam Wise2 and Subhash Mahajan1; 1Sandia National Laboratories, Albuquerque, New Mexico; 2Department of Chemical and Materials Engineering, Arizona State University, Tempe, Arizona.

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The optical constants and polarized optical properties of amorphous AlN nanopowders having wurzite structure with an average size of 80 nm are presented. The wurzite structure has six Raman active modes and observation of these modes depends on the Raman selection rules. In powders, due to the random orientation of the crystallites, the normal selection rules are relaxed, so in principle, all the modes should be observable. Additionally, upon reaching resonance some of the modes are expected to have strong intensity.

In our experiments we utilized the following laser lines: UV lines at 244 nm (3.08 eV) and 325 nm (3.81 eV), and the visible lines at 457 nm (2.71 eV), 488 nm (2.54 eV), 514 nm (2.41 eV), and 633 nm (1.96 eV). For ZnO, we found that the E2(LO) mode is the strongest mode for UV laser excitation at 325 nm. As for AlN, the E2(LO) mode is found to be the strongest mode for all the laser lines utilized in this experiment. The E2(LO) mode becomes detectable only for the deep UV excitation at 244 nm. The Raman mode behavior of the AlN and ZnO nanocrystallites is discussed in terms of the Frohlich interaction, absorption length, and resonant and non-resonant Raman selection rules.

Frequency magnetron sputtering onto silicon (111) and glass substrates has been investigated. The optical constants of a-AlN (in the range 200–1400 nm), n–GaN (in the range 400–1400 nm), and n–a-InN (in the range 1.92–2.92, 2.92–2.46, and 1.92–2.40, respectively) have been determined using the Cauchy–Urbach model while the optical constants of a-InN (in the range 300–1400 nm) are determined using the Tauc–Lorentz model. Refractive indices of AlN, GaN, and InN are found to be in the range 1.92–2.92, 2.92–2.46, and 1.90–2.40, respectively while the extinction coefficients are found to be in the range 0.0–0.55, 0.005–0.37, and 0.0–0.58 respectively. Analysis of the absorption coefficient shows the optical bandgap of these thin films to be 5.9 ± 0.05, 3.45 ± 0.05, and 1.67 ± 0.05 eV, respectively. From the angle dependence of the p-polarized reflectivity we deduce Brewster angles of 61° (a-AlN), 63° (a-GaN), and 64° (a-InN) and principal angles of 65°, 67° and 69°. Measurement of the polarized optical properties reveals a high transmissivity and very low absorptivity for all three thin films in the visible and near infrared regions.

GaN is a promising material for use in nano-scale photonic switches at room temperature (RT). Recently, many different techniques have been used to fabricate high-quality GaN films, such as MBE and MOCVD. Although high-quality GaN has been fabricated at high temperatures above 1300 K, such high temperatures can be detrimental to synthesis of GaN on more temperature-sensitive substrates due to the intense reactivity between NH3 and the substrate. Hence, the development of low-temperature synthesis of high-quality GaN would allow us not only to fabricate abrupt heterointerfaces between the substrate and the GaN layer but also to reduce the defects due to the change in the thermal expansion coefficients.

The influence of strain on semiconductor thin film morphology has been studied for various alloys [1,2]. Surfaces were found to be flat under tension but rough under compression. Based on molecular dynamics simulations, the authors demonstrated that the terrace structure was traceable to the structure of different surface steps and their response to different types of strain. GaN-based semiconductors have found many commercial applications in a variety of high-brightness optoelectronic and high power electronic devices, such as light emitting diodes (LEDs), laser diodes (LDs), and detectors. To obtain increased brightness from LEDs and LDs, a highly uniform and smooth surface of epitaxial GaN films is required. In particular, control of surface morphology is one of the most important targets in fabricating light-emitting devices because surface macrostep patterns can produce a large propagation loss. In addition, when properly employed, strain engineering has played a major role in the efficiency enhancement of InGaN LEDs and LDs since it is possible to control the inherent properties of some of these materials (i.e., piezoelectric fields) and optimize device performance and reliability [3]. In this study, we investigate the GaN substrate morphology on 2 inch diameter GaN epitaxial films grown using a Veeco TurboDisc substrates due to the difference in the thermal expansion coefficients. PhotocVD (PCVD) growth is a technique that can reduce the growth temperature by yielding the reactive radicals Ga and N via photolysis of their precursors. Although, the photolytic synthesis of GaN has been demonstrated at 800 K, its detailed optical properties remain unclear. We report here on the dependence of PL spectra on the V/H ratio of nanocrystalline GaN films deposited at RT using PCVD. GaN nanocrystals 100 nm thickness were grown on a sapphire (001) substrate at RT. We used TMG and semiconductor grade NH3 as the III and V sources, respectively. H2 was used as the carrier gas for the TMG. The partial pressure of NH3 was fixed at 500 Torr, so the V/H ratio (g) was varied by changing the partial pressure of TMG. We used a frequency-quantum-doubled Nd:YAG laser (λ = 213 nm) as the light source for the photodissociation. The PL spectra of the samples were excited using a CW HeCd laser (λ = 325 nm). To check the atomic composition of the sample, X-ray photoelectron spectroscopy (XPS) was used after removing a surface layer of the sample. The RT PL spectra for samples fabricated in the range of 10 < g < 50 show a broad peak with a full width at half maximum (FWHM) of 0.5 eV. It is observed that the intensity of the PL peak becomes larger, and the deposited film is very smooth, corresponding to the oxygen defect-related emission of hexagonal GaN. In contrast, a sharp peak (FWHM of 100 meV) from 3.26 to 3.32 eV is observed for the samples with g < 5000. Furthermore, the low-temperature (5 K) PL spectra of the samples with g > 50000 show two dominant PL peaks at 3.26 and 3.31 eV, which can be ascribed to transitions from the quantum confinement of carriers in cubic inclusions within the hexagonal material. XPS analysis was used to check the atomic composition ratio of Ga and N. The atomic composition ratio of the nitrided gallium was determined using the relative sensitivity factor; gallium, 54.5%; nitrogen, 45.5%. This implies that the deposited film was well nitrided by the PCVD due to the large V/H ratio, even at RT.
operation of a true Bloch oscillator (BO) in a continuous wave mode is severely limited by formation of electrical domains resulting from d-c-NDC. A solution to this problem is to use p-doped silicon c-dc-NDC while preserving negative dynamic conductivity near the Bloch frequency. The corresponding BO regimes require a high degree of coherence of the carriers and were discussed with respect to the high-mobility GaN/AlGaN superlattices in Ref. [2]. In this work we study possible THz generation in a diffusive quasi-static regime below the critical field where neither Bloch instability nor domain formation is possible. In this regime of operation, multiple scattering events during a single de-phase period result in the carrier oscillations. We found that the positive d-c conductivity and high-harmonics 2f (3f)
NDC occur at the same time: this means that high harmonics in an SL are generated not only because of the frequency conversion typical to a Stark-modulated Gunn diode, but due to the instability in the regions where corresponding nonlinear conductivity is negative and d-c conductivity is positive. This allows generation of a sub-millimeter wave signal (1 THz in second harmonic) in the media stable with respect to domain formation.


E11.10 Crystalinity and Polarity of III-V Nitride Semiconductors Grown on ZnO - W. Ohgaki1, K. Kondo1, N. Ohashi1, S. Sugimura1, Isao Sagakuchi1, Katusi Mase2, Mitsuhiro Sato1,2,5, and Hajime Hana1,4, 1National Institute for Materials Science, Tsukuba, Japan; 2NIMSWave Inc., Gunma, Japan; 3Tokyo Denpa Co., Ltd., Tokyo, Japan; 4Kyushu University, Fukuoka, Japan; 5Tokyo Institute of Technology.

Zinc oxide (ZnO) is a possible material for lattice-matched substrate for growth of III-V nitride semiconductors. In this study, we investigated growth condition dependence of polarity and crystalinity of GaN based alloys grown on single crystalline ZnO substrates. We used hydrothermally grown ZnO single crystals as substrates, 10x10 and 20x20 cm in size. The substrates were polished with chemically and mechanically-polishing and finally flattened by thermal annealing. The samples were prepared with molecular beam epitaxy method using r.f. plasma gun for a nitrogen source. We examined growth of GaN and InN on polar or nonpolar single crystalline ZnO substrate. The crystalinity was characterized by x-ray diffraction and TEM observations. Polarity of the crystals was determined by ion scattering spectroscopy. A notable feature at ZnO/GaN interface was change in polarity at this interface. For example, GaN grown on oxygen side of ZnO/ZnO buffer layer had zinc polar face. This means GaN of cation polarity can be obtained on ZnO of anion polarity. A TEM observation indicated that this change in polarity at ZnO/GaN interface did not induce degradation of crystalinity of GaN films. It was investigated that optimizing growth conditions of, particularly, buffer layers. We will also present high quality InN films grown on ZnO substrates.


Semi-insulating GaN templates are necessary for electronic devices in order to ensure electron current component is pinched-off, low loss, and low inter-device cross-talk. Results for semi-insulating GaN have been reported in the past, but further work is necessary to achieve this objective in a satisfactory way for device applications. As a first step, we examined the properties of OMVPE grown GaN by adjusting only the final growth temperature and NL thickness. We have achieved sheet resistance of 10^3 ohm/square on a series of 2 µm thick layers of GaN on sapphire substrates. We have used a step-growth process with a 15-20 nm GaN NL deposited at 1060° C and the main GaN layers grown between 1005-1045° C. Samples with both 26 and 30 nm NL thickness were grown with main growth temperature of 1033° C. In order to test the effects of the NL thickness, the growth temperature was also fixed at 1033° C and the NL was varied between 15-50 nm. The best results were seen for the 26 nm NL thickness at 1033° C, giving a sheet resistance of 10^3 ohm/square. The XRD thickness dependence of the 26 nm NL thickness samples show a steady increase in (1012) FWHM with increasing thickness, indicating higher edge dislocation density at higher growth temperatures. The experiments above lead to the conclusion that the final growth temperature and NL thickness are critical parameters affecting the overall resistivity of the GaN epilayer. In addition, the in-situ reflectance recovery time directly relates to the NL annealing schedule. The recovery time can be used as a figure of merit for in-situ evaluated materials. Both low resistance and high resistance GaN templates were used to grow Al0.3Ga0.7N/GaN HFET structures with a nominal 25 nm barrier thickness. The room temperature mobility of the low and high resistance GaN was 1200 and 1033 cm^2/Vs, respectively (sheet charge was 1.0x10^13 cm^-2 for both samples). X-Ray Reflectivity gave interface roughness of the low and high channel HFET structures 1.1 nm and 1.4 nm, respectively. Despite the increase in dislocation density, the high resistance channel shows both improved interface roughness and 2DEG mobility compared to the low resistance channel. Device results for transistors fabricated on both types of material will also be presented.

E11.12 Abstract Withdrawn E11.13 Pressure dependence of elastic constants in wurtzite and zinc-blende nitrides and their influence on the optical pressure coefficients in nitride heterostructures. Slawomir Pawel Lepkowski1 and Jacek A. Majewski2, 1Unipress, High Pressure Research Center, Polish Academy of Sciences, Warszawa, Poland, 2Walter Schottky Institute, Technische Universitaet Munchen, Garching, Germany.

The electronic and optical properties of semiconductor heterostructures depend crucially on the strain arising from the lattice mismatch. Commonly, the strain effects in quantum structures (quantum wells, wires or dots) are described using the standard elasticity theory with elastic constants independent on the strain (so-called linear theory) in the absence of piezoelectric effect. There are cases, however, where this simple approach is insufficient. Nonlinear elastic properties of GaAs and InAs have recently attracted significant attention. Frogley et al. proposed that pressure dependence of elastic constants in GaAs and InAs are required to explain anomalously small pressure coefficient of band-gap in strained InAs/GaAs layers [1]. Ellaway et al. calculated pressure dependences of elastic constants for InAs and discussed their influence on the properties of InAs/GaAs quantum dots [2]. In this work we have studied the nonlinear elasticity effects for the case of III-N compounds. Particularly, we have determined the pressure dependences of elastic constants in wurtzite and zinc-blende InN, GaN, and AlN by performing ab-initio calculations in the framework of plane-wave pseudopotential implementation of the density-functional theory [3]. We have found significant and almost linearly increasing dependences on pressure for C11, C12 in zinc-blende phase and C11, C12, C13, C23 in wurtzite phase for all studied nitrides. Much weaker dependence has been observed for C44 in both wurtzite and zinc-blende phases. It turns out that the knowledge of the pressure dependence of the elastic constants is essential for determination of pressure coefficients of light emission (1) in InGaN/GaN and GaN/AlGaN quantum wells (QWs). We have found that for nitride QWs one may expect more than 10% reduction in due to increase of elastic constants with pressure. This effect is especially important for 001 cubic InGaN/GaN QWs in which is not affected by piezoelectric polarizations. We illustrate it with an example. In Ref. 4, experimental values of for cubic In0.1Ga0.9N/GaN QWs with different QW widths were reported. They were compared with theoretical results obtained using a modified version of the linear elastic theory. Significant disagreement between experimental and theoretical results was found [4]. In the present paper, we demonstrate that taking into account the pressure dependence of elastic constants for GaN and AlN decisively improves the agreement between calculated and experimental values of in cubic In0.1Ga0.9N/GaN QWs. The role played by the so-called non-linear elasticity in other nitride heterostructures will be also discussed. [1] M.D. Frogley, J.R. Dorens, and D.J. Dunstan, Phys. Rev. B 66, 134101 (2002) [2] S.W. Ellaway and D.A. Faux, J. Appl. Phys. , 92, 3007, (2002) [3] G.Kresse and J. Furthmuller, Phys. Rev. B 54, 11169, (1996) [4] T.Suzuki, H. Tessler, S.P. Lepkowski, P.Perlin, T.Kitanura, Y.Ishida, H.Okumara, S.F. Chichibu, Appl. Phys. Lett. 81, 285, (2002).

E11.14 Modeling of elastic, piezoelectric and optical properties of vertically correlated GaN quantum wells. Slawomir Pawel Lepkowski1,2, Grzegorz Jurczak2, Pawel Dziubow2

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E11.17 Scanning probe investigation of surface charge and surface potential of GaN-lateral polarity heterostructures.

Brian J. Rodriguez,1 Alexei Gorbunov, W. Yang1 and Robert J. Nemachek1

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The determination of surface charge and the screening mechanisms of III-nitrides are fundamental issues which affect the design and fabrication of devices based on polarity effects. In this study, scanning Kelvin probe microscopy (SKPM) and electrostatic force microscopy (EFM) have been employed to measure the relative surface potentials and surface charge densities of patterned Ga- and N-face GaN epitaxial layers. The surface charge density of a GaN-lateral polarity heterolayer (LPH) was evaluated by determining the bias that equilibrated the electrostatic force due to both polar faces. These measurements are made before and after an HCl wet chemical treatment in order to address the role of adsorbed charge on polarization screening in GaN. It has been found that while the Ga-face surface appears to be unaffected by the surface treatment, both the surface charge and the surface potential of the N-face GaN were reduced as a result of the surface treatment. Unlike oxide surfaces, which have been found to be primarily screened by adsorbed species, the GaN is primarily screened by internal charge.

E11.18 Electrical Properties of AlGaN/GaN Superlattices Grown by MOVPE for Application to High Electron Mobility Transistor.

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Realization of low resistance Ohmic contact and low leakage Schottky contact is essential for the fabrication of high performance field effect transistor (FET). In AlGaN/GaN high electron mobility transistor (HEMT) structures, a doped AlGaN-barrier shows good Ohmic property, but also shows poor Schottky behavior, while an undoped AlGaN-barrier shows low leakage current but shows poor Ohmic property. We found that this controversy can be overwhelmed by using superlattices as the barrier layers. AlxGaxN/GaN-SLs with different barrier/well thicknesses are grown on GaN/LT-AIN/sapphire using MOVPE. Modulation doped structures are also grown. X-ray diffraction reciprocal space mapping analysis reveals that the AlxGaxN/GaN-SLs are coherently grown on underlying GaN layers. Hall effect measurement at room temperature shows relatively high electron mobility of 1,366 cm²/Vsec for a sample having Al0.3Ga0.7N (3μm)/75μm-SLs barrier. Schottky and Ohmic contacts are formed on top layer of the SLs using Ni/Al and Ti/Al as the electrode metals, respectively. Leakage current of the undoped SLs under reverse bias is extremely smaller than that of the AlGaN-barrier. However, Ohmic property is quite poor. By introducing modulation-doping, Ohmic contact resistance drastically decreased while leakage current is kept small. A HEMT structure having modulation doped Al0.3Ga0.7N-Ni/AlN SL is fabricated. It exhibits the good pinch-off property, the maximum transconductance is 7μS/mm with gate width and length of 3 μm and 150 μm, respectively.

E11.19 Compositional Ordering in InxGa1-xN and Its Influence on Optical Properties, Zuzanna Lilestone-Webov1, D.N. Zakhrov2, K. M. Yu1, J. Wei1, S. Litt1, J. W. Ager III1, Wladek Wysoczynski1, E.E. Haller1, W. Lu3 and W. J. Schaff1, 1Materials Science Division, Lawrence Berkeley National Laboratory, Berkeley, California; 2Materials Science and Engineering, University of California, Berkeley, California; 3Department of Electrical and Computer Engineering, Cornell University, Ithaca, New York.

Transmission Electron Microscopy (TEM) and optical measurements of samples containing InGaN grown by MOVPE were performed to study the influence of In compositional ordering in InxGa1-xN films. The TEM was performed on a Leo 912AB 200 kV microscope and the optical measurements were performed using a Perkin-Elmer Lambda 900 spectrophotometer. The estimated period of ordering was about 5 nm. The ordering appears...
on the same plane where we had previously observed formation of V-defects (pinholes) in InGaN. Also, there was a theoretical prediction that predicts the possibility of dislocations on these polar planes. The relationship between structural properties, compositional ordering, and optical properties of the In1-xGaN films, in particular the presence or absence of a Stokes shift between absorption and photoluminescence, will be discussed. This work is supported in part by the U.S. Department of Energy under contract No. DE-AC03-76SF00098.

**E11.20** Sub-micron Selective Area Growth of GaN Islands on GaN, AlN and Sapphire Substrates. Fatemeh Shahdadpour-Sandvik,
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Azar Alizadeh,
Surya Ganti,
Seth T. Taylor and Steven F. LeBouef,
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General Electric Global Research, Niskayuna, New York.

We have investigated through experimentation and modeling the mechanism of selective area growth of sub-micron GaN structures on substrates with varying lattice mismatch (in relation to GaN).

Metalorganic chemical vapor deposition (MOCVD) growth was performed on sapphire, GaN and AlN substrates, which resulted in differing strain levels in the subsequent epitaxial material. A 100 nm thick SiO2 layer was deposited on these substrates using plasma enhanced chemical vapor deposition. Conventional UV lithography and reactive ion etching techniques were used to generate 700 nm diameter circular features (through the SiO2 layer) with center-to-center spacing of 1.5 microns in the SiO2 layer. We will show that under identical MOCVD growth conditions (temperature, V/III ratio), the growth of GaN is a function of lattice mismatch and strain, resulting in variation in growth rate and faceting of GaN islands on various substrates. Selective area growth of GaN on low strain substrates, such as GaN and AlN, results in pyramidal island morphology, while growth on strained substrates such as sapphire gives rise to sub-micron prismatic GaN islands. The morphology, crystalllography and optoelectronic properties of these sub-micron GaN crystals were characterized by SEM, TEM, CL and room temperature PL. We have analyzed the effect of substrate strain on adatom binding energies and Ehrlich-Schwoebel barriers using empirical tight binding potential calculations. For GaN grown on GaN (unstrained substrate), faceting is controlled by MOCVD growth conditions, which in this case leads to pyramidal crystals. In contrast for GaN grown on sapphire (largely strained case), the tensile strain in GaN increases the Schwoebel length ($l_e = \exp(E_s/kT)$) promoting prismatic island growth. This model qualitatively explains our experimental observations.

**E11.21** Transmission Electron Microscopy Study of an Epitaxial Gate Oxide for III-N Semiconductor Structures. Yosuke Safiuchi,
X.-Q Liu,
J. K. Markel,
D. W. Barlage,
M. A. Johnson,
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An effective gate insulator for compound semiconductors has been a challenging goal for the materials research community over nearly 40 years. Recent developments related to the epitaxial deposition of complex gate oxides have shown promise with the demonstration of enhancement mode high electron mobility transistors (e-mode HEMTs). In this work, gate oxide layers deposited on III-V semiconductors for field effect transistors (FETs) are examined using transmission electron microscopy (TEM) to identify the structure of the oxide/semiconductor interface. The Z-contrast atomic resolution and diffraction contrast images of the cross-sectional structures as well as the corresponding selected area diffraction patterns for the first time reveal a crystalline nature of the interface between a functional gate oxide and III-V semiconductor. The crystalllographic correlation between the gate oxide and the semiconductor films corresponds to the observed changes during oxide epitaxy by reflection high energy electron diffraction (RHEED). The surface morphology of the FET structures is investigated by atomic force microscopy both before and after gate oxide deposition, and the structural resolution related to their DC electrical characteristics. With the underlying GaN/InGaN heterojunction grown by Metal Organic Chemical Vapor Deposition (MOCVD) on sapphire, these MOSFET devices exhibit the characteristics of a substantially unpinmed interface, including the capacity for significant charge accumulation and transconductance at positive gate voltages. TEM analysis of the structure of the oxide/semiconductor interface and correlation with the device characteristics will be presented.

**E11.22**

**E11.23** Fabrication of Silicon Nitride Film using Pure Nitrogen Plasma Generated near Atmospheric Pressure for III-V Semiconductor E4ctor Fabrication. Takeshi Yoshimura,
Hiroya Kitahata,
Ternuoy Uchera,
Noritomi Fujimura;
Department of Applied Materials Science, Graduate School of Engineering, Osaka Prefecture University, Sakai, Osaka, Japan;
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In recent years, nitrogen plasma has been intensively studied due to the promising applications for the fabrication III-V nitride semiconductors such as GaN, AlN and InN. Low electron cyclotron resonance (ECR) plasma and radio frequency (rf) plasma sources are usually used and operated at the pressure ranging from $10^{-3}$ to $10^{-6}$ Torr, which may yield the nitrogen defects in these nitrides. Therefore, we have tried to apply nitrogen plasma generated near atmospheric pressure for III-V nitride semiconductor processes. However, it is very difficult to maintain the stable and non-equilibrium nitrogen plasma because the transition time from glow discharge to arc discharge drastically decreases with increasing the pressure. Recently, some of our authors have developed the plasma source that maintains the stable discharge in pure nitrogen without helium at atmospheric pressure by applying the alternative pulsed voltage. In this study, as first step to apply for III-V nitride semiconductor processes, the nitridation of silicon was performed and investigated. A nitrogen plasma was generated by applying an alternative pulse with a voltage of 3 kV, a frequency of 30 kHz and a pulse width of 5 μm between two parallel electrodes at a fixed flow (10 l/min) of high-purity nitrogen (99.9999%). From optical emission spectroscopy, strong emissions from the $N_2$ and positive series and weak emissions from $N_2$ were observed. This indicates that the $N_2$ ($\chi_2$) state is effectively created in the nitrogen plasma generated near atmospheric pressure. Nitridation was performed at the fixed pressure of 500 Torr. Other process parameters such as the substrate temperature and nitridation time were varied from 25 to 500 °C and for 0.5 to 10 min, respectively. The thickness of the formed nitride was almost identical and the nitridation reaction was independent on the substrate temperature and nitridation time. The thickness of the silicon nitride was 200 nm at the substrate temperature above 25 °C, and our authors have developed the plasma source that maintains the stable discharge in pure nitrogen without helium at atmospheric pressure by applying the alternative pulsed voltage. In this study, as first step to apply for III-V nitride semiconductor processes, the nitridation of silicon was performed and investigated. A nitrogen plasma was generated by applying an alternative pulse with a voltage of 3 kV, a frequency of 30 kHz and a pulse width of 5 μm between two parallel electrodes at a fixed flow (10 l/min) of high-purity nitrogen (99.9999%). From optical emission spectroscopy, strong emissions from the $N_2$ and positive series and weak emissions from $N_2$ were observed. This indicates that the $N_2$ ($\chi_2$) state is effectively created in the nitrogen plasma generated near atmospheric pressure. Nitridation was performed at the fixed pressure of 500 Torr. Other process parameters such as the substrate temperature and nitridation time were varied from 25 to 500 °C and for 0.5 to 10 min, respectively. The thickness of the formed nitride was almost identical and the nitridation reaction was independent on the substrate temperature and nitridation time. The thickness of the silicon nitride was 200 nm at the substrate temperature above 25 °C, and the thickness of the formed nitride was 200 nm at the substrate temperature above 25 °C. In this work, we have presented a detailed study of the misfit dislocation structure in InGaN/GaN heterostructures with a large lattice mismatch. A sample was characterized by the growth of MOVPE on GaN substrates with a thickness of 300 nm. Arrays of dislocation defects were observed in a six-fold symmetry are observed at the heterojunction interface. The dislocation lines are approximately parallel to the substrate. Electron diffraction contrast analysis indicates that the Burgers vector component on the basal plane is parallel to the [110] direction. This indicates that the dislocations are edge type, irrespective of the presence of a c-component. Possible dislocation reactions leading to the observed arrays will be presented.

**E11.24** Structure of Misfit Dislocations Resulting from Non-Basal Plane Slip in InGaN/GaN Heterostructures. Rong Liu,
S. Srinivasan,
J. Meil,
F. A. Ponce,
T. Mukai,
Shinji Tanaka;
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InGaN films usually grow pseudomorphically on GaN because the basal-plane slip system is inactive in standard c-plane growth geometry. However, at higher indium compositions, the misfit strain can exceed a critical value and activate certain non-basal slip systems. This is particularly the case when the threading dislocation density in the GaN is very low. Misfit dislocation arrays have been observed in such materials, but their structure is complex and has not been clearly understood. In this report, we present a detailed study of the misfit dislocation structure in InGaN/GaN heterostructures with a large lattice mismatch. The sample consists of 100 nm In1-xGaxN 83N film grown by MOVPE on GaN free-standing substrate (with a threading dislocation density of $10^3$ cm$^{-2}$). Arrays of misfit dislocations distributed in a six-fold symmetry are observed at the heterojunction interface. The dislocation lines are approximately parallel to the basal plane. Electron diffraction contrast analysis indicates that the Burgers vector component on the basal plane is parallel to the [110] direction. This indicates that the dislocations are edge type, irrespective of the presence of a c-component. Possible dislocation reactions leading to the observed arrays will be presented.

**E11.25** Generation of Radial Dislocation Arrays at Surface Pits in InGaN/GaN Heterostructures. Rong Liu,
S. Srinivasan,
J. Meil,
F. A. Ponce,
T. Mukai,
Shinji Tanaka;
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We have studied the microstructure of InGaN epilayers grown on...
free-standing GaN substrates with a threading dislocation density of 10^7 cm^-2. The InGaN layers have thickness of 100nm and indium concentration x=1/5, below which AIN-rich thick GaN layers on AIGaN layers result in T_c = 1250K. However, in the barrier-doped samples the QW characteristics basically disappear. Also, the clustering phenomena are normally stronger in the samples of higher average indium contents. Based on this, we calculate the indium contents in the well layers of different samples. It is found that the un-doped samples tend to have lower average indium contents, compared with well- and barrier-doped samples, assuming that other growth conditions are the same. This trend can be interpreted as the different indium incorporation efficiency under different doping and hence strain conditions.

E11.26 Intrinsinc Stress Evolution during the MOCVD Growth of GaN on (111) Si Using Graded AIGaN Buffer Layers.

A common problem encountered in GaN growth on Si substrates is crack formation resulting from residual tensile film stress. Previous studies have reported that film cracking can be reduced in micrometer-thick layers by employing a compositionally graded AIGaN buffer layer, however, the effect of buffer layer thickness and grading profile on film stress is not well understood. In this study, in-situ wafer curvature measurements were used to monitor stress evolution during MOCVD growth of GaN on (111) Si using graded AIGaN buffer layers. The incremental growth stress was observed to change from tension to compression during the growth of the graded buffer layer. The incremental compressive stress was found to be in excess of 1 GPa which is more than the tensile stress expected in these layers upon cooling from the growth temperature (1100°C) based on thermal expansion mismatch. When compositional grading was stopped during the compressive segment and growth of a constant composition AIGaN layer was continued, a transition to tensile stress was observed. Once the gradation was resumed the stress reverted back to compressive. A combination of compressive stress generation due to the change in lattice constant and tensile stress generation due to lateral growth are used to explain these results. During growth of the subsequent GaN epilayer the incremental stress changes to tensile similar to that observed during growth of GaN on (111)Si using an AIN buffer layer. However, both, the magnitude of the final tensile stress and the thickness at which this transition takes place were found to be dependent on the thickness and compositional gradient of the buffer layer. By varying these two parameters GaN epilayers with almost zero tensile growth stress were deposited. It was observed that the crack density in 1 mm thick GaN layers on AIGaN layers > 1 mm in thickness is significantly lower than in GaN layers on an AIN buffer layer. It is believed that the combination of a thick buffer layer that is in compression, in conjunction with a GaN layer that is in net lower tension is responsible for the reduction in crack density.

E11.27 Abstract Withdrawn

E11.29 The Critical Height for Dislocation Annihilation and Recombination in GaN Columns Deposited by Patterned Growth.

Vertical confinement devices based on the III-V nitride family of semiconductors have seen considerable success in optoelectronic applications. However, these devices will require further development to have an impact in high performance and high power laser diodes and substrates. The need for new bonding and integration techniques has led to a new interest in wafer bonding of substrates. In this study, we measured the critical height for the onset of relaxation-induced dislocation annihilation and recombination in patterned GaN columns. A combination of stress measurements obtained from X-ray diffraction rocking curves and transmission electron microscopy (TEM) was used to understand and optimize the reduction of dislocation density in this structure. We have developed a simple closed-form analytical model for predicting the critical column height for the onset of the reduction in the dislocation density. This model uses the tendency for the strain energy from grain misalignment to decrease with column height, therefore allowing the unlocking of tilt boundaries defined by threading edge dislocations as the column height increases. This unlocking mechanism is driven by dislocation line tension in an attempt to similar to that developed by Matthews and Blakeslee for defining the critical thickness in heteroepitaxial layers. Among the predictions of our model is that the critical column height for the onset of dislocation density reduction is proportional the product of the width of the hexagonal column and the grain size of the GaN film. For a column that is twenty microns in width with a 0.1-micron grain size, the critical height for the onset of relaxation-induced dislocation annihilation is on the order of a micron. This prediction is in agreement with preliminary observations of 20-micron wide columns: enhanced dislocation annihilation occurs for a column 2 microns in height, and not in a column 0.5 micron in height.

E12.10 Vibrational Entropy-Induced Ordering Predicted in the System Al1-xGa xN.

First principles phase diagram calculations were performed for the system AlN-GaN. The Vienna ab-initio simulation package (VASP) was used to calculate total energies for wurtzite-structure AlN and GaN, and formation energies for spin-orbit-split polar wurtzite and metastable nonpolar wurtzite phases. The alloy theoretic automated toolkit (ATAT) was used to fit two cluster expansion Hamiltonians; one excluding and one including the excess vibrational entropy, $S_{vib}$. Excluding $S_{vib}$, one predicts a symmetric miscibility gap with composite temperature, $T_c \approx 290K$. Including $S_{vib}$, one predicts an ordered phase based on $\text{AlN}_2\text{GaN}$ stoichiometry with: 1) a eutectoid temperature, $T_s \approx 50K$, below which AlN-rich and GaN-rich alloys coexist; 2) a critical temperature for disordering, $T_c \approx 225K$ (this number is highly uncertain, i.e. ±30K).
an undetermined crystal structure. Sharply peaked miscibility gaps between the AlGaN and AIN phases suggest that a tricritical point exists, hence giving information about the internal piezoelectric field and indium composition homogeneity. Moreover, these samples have been electrically contacted by simple In contact. They showed strong electroluminescence at room temperature confirming the other luminescence data and demonstrating that even on these side facets, regular pn junctions can be fabricated. Therefore we conclude, that this technology may pave the way to nitride based optoelectronic devices with reduced internal piezoelectric fields [11] T. Takeuchi et al., Jpn. J. Appl. Phys. 39 (2000) 413.

E11.32

Electroluminescence from GaN Quantum Wells Grown on Non-Uniform GaN Stripes

Barbara Neubert1, Frank Habel1, Peter Brueckner1, Martin Schirra2, Klaus Thonke2 and Ferdinand Schoich2

Due to their strong polarity, group III nitrides show large piezoelectric constants along the [0001] axis. Therefore strong piezoelectric fields are induced in biaxially strained GaN quantum wells grown on such [0001]-oriented GaN. This gives rise to a spatial separation of the electron and hole wave functions what hampers their radiative recombination. Calculations from other groups [1] have shown, that a higher probability for radiative recombination can be expected for quantum wells grown along directions other than the most commonly used [0001], thus potentially leading to improved optical characteristics for light emitting devices. We fabricated a latticemismatched GaN quantum well on a SiC substrate by MOVPE. The electroluminescence was measured by photoluminescence and cathodoluminescence, hence giving information about the internal piezoelectric field and indium composition homogeneity. Moreover, these samples have been electrically contacted by simple In contact. They showed strong electroluminescence at room temperature confirming the other luminescence data and demonstrating that even on these side facets, regular pn junctions can be fabricated. Therefore we conclude, that this technology may pave the way to nitride based optoelectronic devices with reduced internal piezoelectric fields [11] T. Takeuchi et al., Jpn. J. Appl. Phys. 39 (2000) 413.

E11.33

Growth of Bulk GaN by Ga Vapor Transport

Phanikumar Konakanapal1, Huqing Wu1, Yun Makarov1 and Michael G. Spencer2,3

Electrical and Optical characterization were also performed on these samples. Hall mobility measurements indicated a mobility of 550 cm²/V·s at 77 K, and 150 cm²/V·s at room temperature. The resistivity was approximately 0.2 Ω cm at room temperature. The optical properties of the GaN films were investigated using photoluminescence spectroscopy. The films exhibited a strong near-band edge emission at 364 nm, with a full width at half maximum (FWHM) of 30 nm. The films were grown on Si(100) substrates and had a thickness of 0.5 mm. The films were found to have a high quality and low defect density, with a root-mean-square surface roughness of less than 0.2 nm. The films were also found to have a high electron and hole mobility, with a peak mobility of 1500 cm²/V·s at room temperature. The films were used as substrates for the growth of GaN quantum wells, and were found to have a high quality and low defect density.
E11-35

Electrical and Optical Properties of 1 MeV-electron irradiated Al$_x$Ga$_{1-x}$N. Michael R. Hogsed$^1$, Mo Ahoujja$^2$, Mee-Yi Ryu$^3$, Yung Kee Yeo$^4$, James C. Petrock$^5$ and Robert L. Hengelkold$^6$.

Several radiation-induced point defects for GaN were characterized. After irradiation with a dose of 6x10$^{16}$ cm$^{-2}$, the CL peak intensity was reduced significantly following irradiation, indicating the occurrence of a radiation-induced effect is on the cubic phase in the GaN substrate. The occurrence of this PL peak is shown to be correlated to the presence of various stacking faults and the mechanism by which they form on both sapphire and SiC substrates will be presented.

E11-36

Comparative Study of GaN Based Light Emitting Devices Grown on Sapphire and SiC Substrates. Stephen Pigge$^1$, Sven Einfeldt$^2$, Claudia Roder$^3$, Detlef Hommel$^4$, Tanya Paskova$^5$ and Bo Monearme$^6$.

GaN based light emitting diodes can be used for a broad spectrum of applications. Still most of the devices are grown heteroepitaxially on sapphire or SiC substrates since there is no existing method for the growth of bulk GaN in adequate size. An alternative solution is to fabricate GaN quasi substrates from thick (several 100 μm up to few mm) GaN layers grown by hydride vapor phase epitaxy (HVPE) on sapphire substrates by separating them from the sapphire substrate after growth. In this study we will compare the characteristics of laser diodes and light emitting diodes grown on GaN substrates is achieved by MOVPE (metal organic vapor phase deposition). The growth rate of the MOVPE technique is tensile strained at growth temperature, whereas the free-standing GaN is nearly stress-free. The influence of the domain structure on the device operation will be discussed.

E11-37

Relationship of Basal Plane and Prismatic Stacking Faults in GaN to Low Temperature Photoluminescence Peaks at 3.4 eV and 3.2 eV. J. Bai$^1$, Michael Dudley$^2$, D. Bhattacharjee$^3$, Li Chen$^4$, Brian A. Skromme$^5$, Philip Hartlieb$^6$, Emily Michaels$^7$, Joseph William Keil$^8$, Brian Wagner$^9$, Uttiya Chowdhury$^{10}$ and Russell Dupuis$^{11}$.

The relationship between the structural and optical properties of GaN is of great interest due to the important optical and electronic applications of this material. The low temperature photoluminescence (PL) peak at 3.4 eV has been attributed to several different structural defects. Another PL peak at 3.2 eV may also be related to structural defects but has not been clearly attributed to any specific defect. In this paper, we present evidence linking the 3.4 eV PL peak to the presence of a thin layer of cubic phase associated with basal plane stacking faults (BSF). This relationship is mainly established by studying a series of ammonothermally-grown GaN bulk crystals. The occurrence and strength of the 3.4 eV peak are found to be related to the BSF type (RI2=1/3<100>), which is observed in these samples. For example, the 3.4 eV peak is shown to be accompanied by the cubic phase present in the BSF, which confirms the relationship. These results suggest that HVPE grown GaN substrates are highly beneficial for the production of light emitting devices especially for high power LEDs used for lighting.
We report the first observation of the resonant photoemission from the Ga 3d states in GaN. The energy distribution curves recorded around the Ga 3p threshold show satellites of the main Ga 3d line [1, 2] related to the 3d$^3$ multiplet. Satellite lines exhibit the resonance for hν ≥ 104 - 112 eV. The measurements were performed in beamline 31 of the synchrotron laboratory Maxlab, which is equipped with the photoelectron emission microscope (PEEM) [3]. GaN single crystals [4] were cleaved under UHV. PEEM is suitable for investigating thin films on substrates with a very small beam spot to get information from very thin platelettes and cleaved surfaces have areas in order of 0.1 x 2 mm$^2$ or less. The constant initial state (CIS) spectra recorded on GaN thin films [5] at the bending magnet beamline U4A of the National Synchrotron Light Source (NSLS). The explanation of resonant photoemission mechanism for materials with fully filled 3d band is based upon strong interaction between the 4s - 4p conduction band and the two bound 3d$^0$ holes resulting from the super-Coster-Kronig process. Resonant photoemission is quasiatomic, however, final state screening is material specific. We have performed detailed measurements in the photon energy range hν = 90 - 120 eV. The 3.6 eV separation of the two main peaks related to the $^3$G and $^3$F terms of the 3d$^3$ multiplet at binding energies 54.6 and 50.0 eV is in agreement with the earlier studies on GaP [1] and GaAs [2]. The two additional weaker features are present in the spectra. The feature at 51.9 eV is related to the $^3$D term, whereas the feature at 55.1 eV was not reported in previous studies. We would like to thank Janusz Kanski for helpful discussions. This work was supported in part by the National Science Foundation under grant numbers DMR-0604504, DMR-0604505, and Office under grant 40125F. [1] T.-C. Chang and D. E. Eastman, Phys. Rev. B 27, 5749 (1988). [2] S. Suzuki, T. Kiyokura, F. Mieda, K. G. Nath, Y. Watanabe, T. Saitoh, and A. Kakizaki, J. Elec. Spectroscopy 114-116, 381 (2001). [3] U. J. Soh, R. Nyholm, C. Törnqvist, and A. Flodström, Rev. Sci. Instrum. 66, 1398 (1995). [4] I. Gregorzy, J. Phys.: Condens. Matter 14, 11055 (2002). [5] D. D. Doppnhiud, E. Iliopoulos, S. N. Basu, and T. D. Moustakas, J. Appl. Phys. 85, 3582 (1999). [6] L. C. Davis and L. A. Feldman, Phys. Rev. Lett. 44, 673 (1980).

**E11.40**
Characterization of AlGaN Active Regions for UV Light Sources by Temperature Dependent Cathodoluminescence and Confocal Photoluminescence Microscopy.


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**E11.42**
Abstract Withdrawn

**E11.43**
Non-Polar GaN/AIN Superlattices on A-plane AlN (500nm) Buffer Layers Grown by RF-MBE.

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The fabrication of GaN/AIN interband transition (ISBT) crystals, in which the piezo-electric field does not exist, is very interesting for the application to 1.55μm ultra-fast and high power optical devices with complicated multi-layered quantum heterostructures. The piezo-electric field sometimes hinders precise design of fine quantum devices such as quantum cascade lasers, high-speed optical switch and wavelength conversion elements. In this investigation, therefore A-plane (11-20) non-polar GaN/AIN quantum heterostructures were grown on R-plane (0001) GaN substrate for suppressing the crystal crack. GaN/AIN superlattices should be prepared on nonpolar buffer layers, but the growth technology of A-plane AIN on R-plane sapphire substrate and the A-plane GaN/AlN superlattices were coincident with the calculated value of (340nm) based on the flat field on the luminescence properties of a commercial Cree, Inc.

**E11.44**
Scanning Electron Microscopy (SEM)-Based Cathodoluminescence (CL) experiments were used to study the influence of piezoelectric fields on the luminescence properties of a commercial Cree, Inc.

InGaN-based Multiple Quantum Well (MQW) X-Bright green Light Emitting Diode (LED) was investigated. CL and SEM images of the piezoelectric field in the InGaN-based device were investigated using SEM-CL peak voltage and carrier generation density (i.e. beam current) dependence studies. Supporting evidence for the existence of a piezoelectric field in the device was determined from forward bias electroluminescence (EL) experiments. A compact SEM-CL spectroscopy system with both polychromatic spectroscopic and panchromatic imaging capabilities was designed and implemented for these experiments. The CL emission peak consisted of a USB2000 Ocean Optics miniature spectrometer coupled with a fiber optic light collection system. The spectrometer is a 2048-element linear CCD array and was configured with a 50 m m, a 600 lines/mm grating, a 350nm-1000nm spectral range for potential applications in UV LED active regions have been produced.

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I'm/hr scans carried over a wide angular range revealed the
the length of
full-width-half-maximum (FWHM) of 14 meV and the core-shell type
from the Ministry of Education, Culture, Sports and Technology and
8:30 AM *E12.1
other process parameters are the keys to control the shape and size of
contacts for blue InGaN light-emitting diodes (LEDs) will be
opportunities. The crystal structure of II-IV-N 2 compounds is
orthorhombic, and when grown on r-plane sapphire can provide a
indices in the visible and NIR portion of the spectrum. Although the
II-IV-N films epitaxially by MOVCD creates interesting
temperatures and pressures are required. The success in growing
properties. Bulk crystals are hard to synthesize because high
processes and their resultant properties. Notably, these 1D
measured in photoluminescence (PL) peaks, are quite sharp and show
high-resolution transmission electron microscopic (HRTEM) images
employed to prove the p-n junction formation along a single nanowire.
rectification properties with diode ideality factors as low as 5 for most
8:30 AM *E12.1 One-Dimension Group-III Nitride Nanostructures: Growth,
Structure, and Their Luminescence and Electrical Properties.
Li-Chyung Chen1 and Kisu-Hsien Chen2; 1Center for Condensed
Matte Sciences, National Taiwan University, Taipei, Taiwan;
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I will present our work on the one-dimensional (1D) III-V
nanostructures such as nanowires, nanotubes, nanobelts, nanocables and
nanoips. In a vapor-liquid-solid process wherein a catalyst is
involved, selection and manipulation of the catalyst together with
other process parameters are the keys to control the shape and size of
the materials. The materials grown are of notable properties. Notably, these 1D
nanostructures are single crystals of high quality in that their
high-resolution transmission electron microscopic (HRTEM) images
show nearly defect-free structures and their band edge emissions, as
measured in photoluminescence (PL) peaks, are quite sharp and show
very weak PL, quenching in comparison to their counterparts in films.
For instance, the InN nanobelts exhibit a PL peak at 0.76 eV with a
full-width-half-maximum (FWHM) of 14 meV and the core-shell type
InN/SiGe nanowires have a PL FWHM of only 7 meV. Notably, these 1D
Cathodoluminescence (CL) corroborated with HRTEM studies reveal that,
upon ion implantation, these 1D nanostructures can have
enhanced dynamic annealing. Meanwhile, a hexagonal-to-cubic phase
transformation in GaN nanowires, irradiated at a medium level of
self-ion, has been observed. Finally, fabrication and characterization
of single-wire field-effect-transistor diodes on an array of narrow field emission
diode and their implications will also be discussed.

9:00 AM E12.2 MOCVD growth and characterization of GaN nanowires.
Gela Kipshidze1, Boris Yuvich1, Jongjin Yun1, Anilkumar Chandulu4,
Vladimir Kuryatkov1, Deeder Aurongzeb2, Mark Holtz2 and Henryk
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We describe controlled and highly reproducible growth of GaN
nanowires on sapphire(0001) and Si(111) substrates using thin Ni or Au
nucleation layers. High quality GaN nanowires were grown by
low-pressure metalorganic chemical vapor deposition with NH3 and
trimethylgallium (TMGa) sources on sapphire substrates.
Reproducible growth of nanowires was achieved by using a growth
sequence that limits gas phase reactions between TMGa and ammonia.
Using this approach we obtained single crystal, well-oriented GaN
nanowires with hexagonal cross-sections. The wires are straight,
with constant diameter and smooth sides. The nanowires grow
selectively from islands of metal catalyst. Characteristic globules
observed at nanowires tips confirm the vapor-liquid-solid (VLS)
mechanism of formation. The growth rate appears largely independent
of the wire diameter, further supporting the VLS mechanism. By
adjusting growth parameters such as the substrate temperature, total
pressure, and the III/V ratio, together with the size of catalyst
islands, we were able to control the diameter of nanowires from 30 to
300 nm. With the growth rate of the order of 1 nm/s, the diameter of
nanowires can be readily controlled up to 2 μm. Structural and
optical properties of GaN nanowires were studied by scanning electron
microscopy (SEM), x-ray diffraction, and cathodoluminescence (CL).
Symmetry of the 268-ω scans carried over a wide angular range revealed
the 0002 and 0004 peaks of GaN and confirm the wurtzite structure
of the nanowires and the c-axis growth orientation. X-ray diffraction
measurements of lattice constants allowed us to determine the
magnitude of the compressive stress in the wires, from 0.075 to 0.17
GPa. Reciprocal space mapping (RSM) performed on samples with
different diameters and lengths of nanowires showed different degrees of
relaxation, consistent with lattice parameter measurements. The
observed RSM broadening along the qx direction is also indicative of
strain in the GaN nanowires. This broadening was reduced for shorter
wires. The nature of the relaxation process will be discussed in terms
of defect formation in nanowires of different sizes. Room temperature
CL spectra showed a single band-edge peak at 3.36 eV (360 nm), with the
slight red shift attributed to sample heating. Detailed measurements of optical properties of our GaN nanowires, focusing on
the size and stress dependence will be presented.

9:15 AM E12.3 Microstructure and Nanoelectronics of Single GaN Nanowire with Well-Defined p-n Junction. Guosheng Cheng,1 Electrical Engineering, Yale University, New Haven, Connecticut; 2Chemistry & Biochemistry, University of California, Santa Barbara, California;
2Materials, University of California, Santa Barbara, California.

We demonstrate the first example of a well-defined p-n junction
fabricated in a GaN nanowire and the systematic investigation of its
transport properties down to 2 K. XRD, Raman Spectrum, HRTEM revealed the
30 nm diameter wires, produced by vapor-liquid-solid synthesis in indium nanoparticle catalyst droplets, are shown to
consist of a good-quality, crystalline, hexagonal GaN inner core
surrounded by an amorphous GaN outer layer. Most wires grow such
that the crystalline c-axis is normal to the long axis of the nanowire.
The p-n junction is produced by turning on a source of Mg (a known
p-dopant) halfway through the growth. The wires show excellent
rectification properties with diode ideality factors as low as 5 for most
nanowires. The temperature dependence of the current-voltage characteristics is consistent with electron tunneling through a
dopant-dependent barrier. P-doped and n-doped GaN nanowires
fabricated under similar conditions invariably produced linear
current-voltage curves, indicating that the observed rectification arises
as a result of the p-n junction and not from a metal-semiconductor
Schottky contact junction. Diode transient response measurement was
employed to prove the p-n junction formation along a single nanowire.

9:30 AM E12.4 VLS Growth of III-Nitride Nanowires and Heterostructures by MOVCD. Jie Su1, Maria Gherasimova5, George Cui2, Jung
Hau1, Steven Lin2, Dragos Ciuparu2, Lisa Pfeiffer2, Ying He3, Arto Nurmikko2, Christine Broadbridge4 and Ann Lehman6; 1Department
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Semiconductor nanowires represent a versatile class of nanoscale building blocks for the assembly of functional electronic and photonic devices, including field-effect transistors, light-emitting diodes and electrical injection lasers. Among the many nanomaterials studied to date, the group III-nitrides represent an especially attractive system for exploration since heterostructures offer the opportunity to tailor the electronic and optical properties of the deposited material. These nanostructures produce light over a large range of frequencies. To this end we report the successful synthesis of well-defined GaN/InGaN/GaN core-shell-shell (CSS) nanowire heterostructures. These new CSS nanowires were grown using metalorganic chemical vapor deposition in which the core nanowire was defined by a nanocylinder-mediated vapor-liquid-solid growth process. Silicon-doped GaN nanowire cores and magnesium-doped GaN outer shells serve as electron and hole injection layers, respectively, into the GaN shell. The CSS structure offers a large injection area for individually addressable optoelectronic devices. These GaN/InGaN/GaN CSS structures represent the first electrically driven, high-brightness, blue nanoscale light emitting diodes.

GaN nanowires are technologically attractive due to a promising combination of the electronic and optical characteristics of GaN with the one-dimensional confinement offered by the nanoscale wire structure. To date, GaN nanowires have been grown by virtually all the known methods for growing GaN nanowires, including vapor-liquid-solid (VLS) growth mode, metalorganic chemical vapor deposition (MOCVD) or metal-organic vapor growth (MBE). In these reports it was shown that a vapor-liquid-solid mechanism using metal catalysts in a hydride vapor phase epitaxy process is proposed for the control of nucleation and growth of heterostructures for the fabrication of quantum structures needed to be explored. There are several reports on the growth of GaN quantum dots on AlN using non-equilibrium growth techniques, e.g., MOCVD or MBE. In these reports it was shown that a vapor-liquid-solid catalytic growth mode can be exploited according to the lattice mismatch of 3% for GaN/AlN. Despite the fact that in the case of thermodynamic equilibrium, no island growth is predicted for the deposition of AIN on GaN, Metal-Organic Chemical Vapor Deposition (MOCVD) may offer a growth window to establish quantum structures on GaN surface. Nucleation studies of the AIN on strained GaN epitaxial films are presented. A novel two step growth process is proposed for the control of nucleation and growth of nanostructures by MOCVD. The formation of nanostructures was investigated as a function of growth temperature, applied III/V ratios, growth rate and the amount of deposited material (deposition time). A controlled temperature gradient and a III/V gradient over the wafer are used to apply the thermal gradient to the wafer surface. The surface morphology, size, and density of the nanostructures were analyzed using Atomic Force Microscopy (AFM). The AFM results showed that the obtained nanostructures varied from diameters of 20 nm to 100 nm and heights from 1.5 nm to 10 nm. The density was controlled within the range $1 \times 10^{11}$ cm$^{-2}$ to $1 \times 10^{10}$ cm$^{-2}$. The formation of quantum structures is attributed to migration controlled epitaxy resulting from the advantages of MOCVD growth. The crystalline quality of the deposited material was examined by X-ray diffraction (XRD) spectroscopy. Furthermore, confirmation is provided by Raman spectroscopy, where the AIN (TG) and A1 (acoustical phonon) modes are observed. However, the energy position of the Raman modes is shifted from the value of bulk AIN. Uniaxial strain and/or alloying with the burted GaN are suggested to cause the observed deviation. The UV optical properties of these devices will be also discussed.
involves one of two typical growth mechanisms. The vapor-liquid-solid (VLS) mechanism utilizes a transition metal catalyst while the vapor-solid (VS) mechanism relies on direct crystallization from the vapor. For VLS the dominant morphology is generally small-diameter nanowire because nucleation and growth are defined by a liquid catalyst particle. In contrast, for VS more varied morphologies, e.g. nanobelt, are possible due to the absence of constraints by the catalyst. Accordingly, numerous groups reported the synthesis of various GaN nanostructures, e.g. nanowire and nanobelt, using the VS type growth methods. To the best of our knowledge, there has been no attempt to understand or control the variation of morphology and crystallographic growth orientation among these structures. Such information would be critically important for building up devices out of these nanostructures, and for tuning the device characteristics given the highly anisotropic physical properties of GaN. In the present work, we studied the morphological evolution of GaN nanostructure, from nanowires to polyhedral crystals to nanobelts, by varying the ammonia flow rate in the catalyst-free thermal reaction of gallium oxide and ammonia at 1100°C. Micro Raman spectroscopy (Renishaw 1000) and powder X-ray diffraction (INEL) confirmed that all morphologies were wurtzite GaN. Scanning electron microscopy (JEOL 6300FV) and high-resolution transmission electron microscopy (JEOL 2000F) revealed both thin smooth-surfaced and thick corrugated nanowires. The growth orientations of most of the smooth ones, as well as the nanobelts, were perpendicular to the c-axis (<0001>), while the corrugated nanowires and the large polyhedra grew parallel to <0001>. We propose that the Ga/N reactant ratio, i.e. reaction condition (N- or Ga- rich), in the vapor phase plays an important role in determining the resulting morphology and growth orientation, based on the observed relationship between the morphology and the characteristic length of [0001] polar surface.

11:15 AM E12.9

Semiconductor nanowires have in recent years received intense attention as promising functional materials. As one-dimensional nanostructures that generally have sub-100 nm diameters and macroscopic dimensions of typically 10 μm or more along the length, their small size in one dimension imposes quantum confinement effects which may be exploited in future devices. Generally such nanowires are characterized in the transmission electron microscope (TEM) to determine their composition, structure and morphology. A key parameter is the growth direction, which is crucial towards an understanding of their functional behavior and growth mechanism, especially for non-cubic symmetries. In the current literature, growth direction is usually determined from a single SAED exposure coupled with the bright field (BF) image. Indices of SAED spots through the 000 beam in a line parallel to the nanowire axis are identified with the growth planes of the nanowire. This approach implicitly assumes that the nanowire axis is orthogonal to the electron beam, which can be easily violated under real experimental conditions. A careful consideration of the experimental geometry during SAED experiments in the TEM indicated the current approach is inadequate. An alternative approach will be proposed that removes the assumption of orthogonality, based on the simple observation that two planes parallel to a cylinder intersect along the cylinder axis. The method is demonstrated for wurtzite GaN nanowires which exhibit different growth directions depending on reaction conditions. The morphology and the underlying crystallographic growth direction were definitively correlated using this method, leading to a detailed growth model for these nanowires. The approach is general and may be extended to any crystal symmetry.

11:30 AM E12.10
Abstract Withdrawn