SYMPOSIUM E

GaN, AlN, InN, and Their Alloys

November 29 - December 3, 2004

Chairs

Christian Wetzel
Future Chips Constellation
Rensselaer Polytechnic Institute
110 8th St.
Troy, NY 12180-3590
518-276-3755

Bernard Gil
Groupe d'Etude des Semiconducteurs
Universite Montpellier II
Case Courrier 074
Montpellier, Cedex 05, F-34095 France
33-4-6714-3924

Michael Manfra
Lucent Technologies
Bell Laboratories
600 Mountain Ave
Murray Hill, NJ 7974
908-582-1137

Masaaki Kuzuhara
Photonic & Wireless Devices Res Labs
NEC Corporation
2-9-1 Seiran, Otsu
Shiga, 520-0833 Japan
81-77-537-8671

Symposium Support
†AIXTRON AG
†Cree, Inc.
†Gatan, Inc.
Lucent Technologies
†Riber, Inc.
†SVT Associates, Inc.
†2004 Fall Exhibitor

Proceedings to be published in both book form and online (see *ONLINE PUBLICATIONS* at www.mrs.org) as volume 831 of the Materials Research Society Symposium Proceedings Series.

* Invited paper

SESSION E1: Lasers and Light-Emitting Diodes I
Chairs: Masaaki Kuzuhara and Christian Wetzel
Monday Morning, November 29, 2004
Back Bay C (Sheraton)

8:30 AM *E1.1
Structural Defects related issues of GaN-based Laser Diodes. Shigetaka Tomiya[1], Motonobu Takeya[2], Goto Shu[2] and Masao Ikeda[2]; [1]Materials Analysis Center, Sony EMCS, Atsugi, Kanagawa, Japan; [2]Shiroishi Laser Center, Sony MSNC DSC, Shiroishi, Miyagi, Japan.

Structural defects affecting the lifetime of GaN-based laser diodes (LDs) on epitaxial lateral overgrown (ELO) 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 origins of the threading 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 zincblende-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
Latest Developments in Blue-Violet Laser Diodes Grown by Molecular Beam Epitaxy. Valerie Bousquet, Matthias Kauer, Katherine Johnson, Stewart Edouard Hooper and Jonathan Heffernan; Advanced Optoelectronic Devices, Sharp Laboratories of Europe, Oxford, United Kingdom.

In the last decade, AlGaInN-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 nitride laser diode in 1996 by Nichia 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 only recently been successful in producing an AlGaInN laser [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 January 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 10μm thick Si doped GaN deposited on a sapphire substrate by MOVCD. The threshold current density (Jth) of the devices was 30kA.cm-2. 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 focussed 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 Resonnance (ECR) plasma etched ridge waveguides, cleaved facets and SiO2/SiN4 high reflective facet coating. With this approach we have reduced the threshold current density to less than 15kA.cm-2 and further progress in device performance will be reported. [1] S. Nakamura, S. Senoh, S. Nagahama, N. Iwasa, T. Yamada, Jap. J. Appl. Phy. 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).

9:15 AM E1.3
265 nm Deep Ultraviolet Emitters. Wenhong Sun, Vinod Adivarahan, Shuai Wu, Ajay Sattu, Ashay Chitnis, Maxim Shatalov and M. Asif Khan; Electrical Engineering, Univ. of South Carolina, Columbia, South Carolina.

Recently several groups including ours have reported deep ultraviolet (UV) light emitting diodes (LED) with emission from 280 nm to 290 nm with dc powers above 1 mW.[1,2] These devices can be used in compact low-cost fluorescence based bio-chemical detection applications. Sub-300 nm emission deep UV LEDs are potentially viable light sources for several germicidal and medical applications such as for air/water purification. However, the LED emission wavelength should be tuned to the peak absorption wavelength of biological objects, which is centered at around 265 nm. Currently mercury lamps are used as the 365 nm radiation source. In this paper we will present our recent work aimed at developing deep UV LEDs with emission at 265 nm as a potential replacement for mercury lamps. These devices were fabricated using AlGaN multiple quantum wells that were deposited over sapphire substrates using low-pressure migration enhanced (ME) MOCVD. As before, we used MEMOCVD grown AlN buffer layers and AlN/AlGaN superalttices to manage strain and allow the deposition of thick $Al_xGa_{1-x}N$ (x>0.6) layers. Due to the difficulty in doping of n $Al_xGa_{1-x}N$ layers (with x>0.6) the ohmic contact formation typically requires high temperature annealing, which degrades the device performance and reliability. Reduction of the annealing temperatures usually leads to deterioration of ohmic characteristics. With improved growth and contact formation procedures we have now succeeded in obtaining deep UV LEDs with emission at 265 nm. For a 100μm x 100μm mesa device the I-V curves exhibit the turn-on voltage of 6 V with series resistance of about 40 Ohm. Packaged LED devices show dc powers of 0.18mW at 70 mA and 1.5 mW at 200 mA pulsed pumping with maximum external quantum efficiencies of 0.07 % under dc and 0.17 % under pulsed pumping. Preliminary results of room temperature reliability studies show only a 20 % output power reduction in 10 hours under 40 mA (400A/cm^2) dc constant current conditions. 1. W. H. Sun, J. P. Zhang, V. Adivarahan, A. Chitnis, M. Shatalov, S. Wu, V. Mandavilli, J. W. Yang, M. A. Khan, to be published in Appl. Phys. Lett. 2. A. J. Fischer, A. A. Allerman, M. H. Crawford, K. H. A. Bogart, S. R. Lee, R. J. Kaplar, W. W. Chow, S. R. Kurtz, K. W. Fullmer, J. J. Figiel, Appl. Phys. Lett. 84 3394 (2004)

9:30 AM E1.4
Growth, Characterization, and Application of High Power III-Nitride Ultraviolet Emitters. Zaiyuan Ren[1], Seong-ran Jeon[1], Maria Gherasimova[1], George Cui[1], Jung Han[1], Hongbo Peng[2], Y.K. Song[2], Arto Nurmikko[2], Ling Zhou[3], Michael Krames[3] and Werner Goetz[3]; [1]Yale University, New Haven, Connecticut; [2]Brown University, Providence, Rhode Island; [3]Lumileds, San Jose, California.

The intense attention in III-nitride research towards ultraviolet light emitting diodes (UV LEDs) with emission wavelength below 360 nm is fuelled by applications including chemical/biochemical analysis, solid-state lighting, high-density optical storage, and covert communication. We report on the design, growth, and fabrication of high power UV LEDs in the 280-340 nm range whose capabilities and utility have been demonstrated in their application to time-resolved fluorescence spectroscopy of organic and biomolecules on sub-nsec time scale. Multiple quantum well active regions are embedded into AlGaN p-n diodes, which are grown on AlN buffer layers on c-axis sapphire substrates. Structural characterizations performed using AFM, XRD, and TEM underline the importance of AlN buffer layers. Devices are processed into small apertures (10-100 um in diameter) and large chips (1x1 mm2) for bio-fluorescence and NLOS communication applications, respectively. Near 340 nm wavelength, we have measured output powers of 1.5 mW for 100 um device aperture at current densities of 1.0 kA/cm2 directly (perpendicular) off the chip under CW injection, corresponding to an extrapolated internal quantum efficiency of 7 10%. Fully packaged, large-area chips with heating sinking and encapsulation exhibit more than 50 mW of optical output at a current level of 1 A under pulsed exicitation (duty cycle 1%). Retaining the basic design yet increasing Al compositions in all layers by around 25%, we are able to demonstrate UV LED operation at 285 nm with negligible defect band emission. At present the forward operating voltage is 1 to 2 volts higher than that in the 340 nm LEDs, and the light output is ten to twenty-folds less, projecting an output performance exceeding mW operation in a fully packaged device. The 340 nm LEDs have been configured into high-speed operation by integrating them with a microwave strip line electrode configuration, whereby a device response of approximately 0.4 nsec has been measured at room temperature. Consequently, these high speed compact UV LED sources have been used to demonstrate time-resolved spectroscopic performance with a key biomolecule NADH, whose fluorescence decay time of approximately 0.5 nsec has been measured, influenced by the solvent environment. The result suggests that, at their present status of development, the sub-350 nm LEDs are nearing fruition in their integration as inexpensive, compact sources in UV-based photonic instrumentation. Research supported by DARPA

9:45 AM E1.5
Multiple-Quantum-Well Design for 280nm Light Emitting Diodes. Jianping Zhang[1], Xuhong Hu[1], Jianyu Deng[1], Alex Lunev[1], Thomas Katona[1], Yuriy Bilenko[1], Remis Gaska[1], Asif Khan[2] and Michael Shur[3]; [1]Sensor Electronic Technology, Inc., Columbia, South Carolina; [2]Electrical Engineering, University of South Carolina, Columbia, South Carolina; [3]Rensselaer Polytechnic Institute, Troy,

New York.

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 and AlN/AlGaN strain-defects management superlattices.[1, 2, 3] For the best effect, we recommend to grow these structures using Migration Enhance Metalorganic Chemical Vapor Deposition (MEMOCVDTM). Thanks to these technologies, milliwatt-power 269nm-290nm LEDs have been achieved.[4, 5, 6, 7, 8] Further improvement on the deep UVLED 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 will report the MQW optimization experiments and discuss the impact on real 280 nm UVLED 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 50A, 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 A, indicating a confinement enhanced optical transition oscillation-strength by narrower quantum wells. The nature that carriers possess heavy effective masses in high-Al-content materials requires very narrow quantum wells for efficient light emitting. 280 nm UVLED 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., Toyoda 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 LD with short wavelength. Both of the development of III-V nitride based LED and its applications are introduced. The MQW with $Ga_xIn_{1-x}N$ well layer is used for our developed LED. Adjusting the "In" chemical content of the well layer can achieve the various wavelength of LED including UV region, blue and green. Our developed "short wavelength LED (TG purple)" with flip chip structure has light output power of over 10mW at 20mA in bare chip condition. The wavelength of TG purple is around 385nm and FWHM is less than 10nm. One of applications of TG purple is the air purifier system which was developed by combining TG purple and the photo-catalyst, which is TiOx. The photo-catalyst is excited by the light from TG purple and decomposes the organic materials such as cigarette's smell. This system was equipped in a car and several applications of this system are expanding in room air conditioners and refrigerators. Another major application of TG purple is a light source of white LED. There were several kinds of white LEDs. The first is white LED which combined 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 are blue phosphor with peak wavelength of 450nm, yellowgreen phosphor with that of 575nm and red phosphor with those of ***nm and ***nm. Color rendering index of "TG True White Hi" is over 90. This value is so high in comparison with 70 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 rendering index and luminous intensity by adjusting various phosphor combinations.

11:00 AM E1.7
Junction Temperature Measurements in Deep-UV Light-Emitting Diodes. Yangang Xi[1], Jingqun Xi[1], Thomas Gessmann[2], Jay M. Shayh[2], JongKyu Kim[2], E. Fred Schubert[1,2], Arthur J. Fischer[3], Mary H. Crawford[3], Katherine H. A. Bogart[3] and Andrew A. Allerman[3]; [1]Physics, R.P.I., Troy, New York; [2]Department of Electrical, Computer, and Systems Engineering, Rensselaer Polytechnic Institute, Troy, New York; [3]Semiconductor Material and Device Sciences, Sandia National Laboratory, Albuquerque, New Mexico.

The junction temperature of light-emitting diodes (LEDs) is a critical parameter that affects the internal quantum efficiency, maximum output power, and reliability. A 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 87.6 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 ±3 °C. The emission peak shift method is also used to measure the junction temperature 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
Effect of GaN Surface Treatment on Optoelectonic Properties of GaN Layers and Light Emitting Devices. James Grandusky, Muhammad Jamil and Fatemeh Shadi Shahedipour-Sandvik; School of NanoSciences and NanoEngineering, University at Albany-SUNY, Albany, New York.

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. Metalorganic 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 HF. The surface morphology of subsequently grown undoped GaN layers showed dramatically different properties in comparing 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 the 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 Kasugai[1], Yasuto Miyake[1], Akira Honshio[1], Takeshi Kawashima[1], Kazuyoshi Iida[1], Motoaki Iwaya[1], Satoshi Kamiyama[1], Hiroshi Amano[1], Isamu Akasaki[1], Hiroyuki Kinoshita[2] and Hiromu Shiomi[2]; [1]Faculty of Science and Technology, 21st-Century COE Program "Nano Factory", Meijo University, Nagoya, Japan; [2]SiXON Ltd., Kyoto, Japan.

Recently, high-efficiency nitride-based optoelectronic devices in the visible short-wavelength region have been developed by the combination of several breakthroughs such as the improvement in crystalline quality using a low-temperature-deposited buffer layer technique, and n- and p-type conductivity controls. Nevertheless, a further improvement in the external quantum efficiency of nitride-based light-emitting diodes (LEDs) is one of the most critical issues. In this report, we present high-efficiency nitride-based LEDs with an extremely high light extraction efficiency using the "Moth eye" structure, which has a 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

[1]. This type of structure is called "Moth eye" structure. Therefore, we call our newly developed novel devices the "Moth eye LEDs". A moth eye LED with a peak wavelength of 480 nm, is composed of a high-temperature-grown AlN layer, a Si-doped n-GaN contact layer, three pairs of GaInN/GaInN:Si MQW active layer, a p-type AlGaN electron blocking layer, a p-AlGaN cladding layer and a p^+-GaN contact layer on a 6H-SiC substrate. Both p- and n-contacts were formed on the surface, and light output was extracted from the bottom of the SiC substrate. The "Moth eye" structure was introduced on the backside of the SiC substrate using the CF_4-RIE technique. By the optimization of etching conditions, we succeeded in 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 average, the output power of "Moth eye LEDs" is approximately 3.8 times higher than that of conventional LEDs at 20 mA. [1] H. Toyoda; opto-electronics contact, Vol. 42, No. 3, (2004), p133.

11:45 AM E1.10
MOCVD Growth of AlGaN for Short-Wavelength UV LEDs. Russell D. Dupuis, Uttiya Chowdhury, Peng Li, Jae-Boum Limb, Jae-Hyun Ryou, Theodore Chung and Dongwon Yoo; School of ECE, Georgia Institute of Technology, Atlanta, Georgia.

Wide-bandgap nitride semiconductor materials have attracted attention for deep ultraviolet (UV) optoelectronic device applications. In this paper, we report on the status of ternary AlGaN-based UV-LEDs emitting at 280 nm. These devices are fabricated from epitaxial layers grown using the low-pressure metalorganic chemical vapor deposition (LP-MOCVD) technology. The epitaxial layers are grown on dual-side polished c-plane sapphire substrate and light was extracted from the back-side of the sapphire substrate. The device structures typically consist of a low-resistivity n-type AlGaN window layer in order improve light extraction while maintaining a low spreading resistance. The typical active region consists of three 10nm Al0.48Ga0.52N:Si barriers with three 5nm Al0.48Ga0.52N:Si quantum wells. The p-side cladding layer structures generally consist of a 20nm p-type Al0.52Ga0.48N:Mg and 20nm Al0.40Ga0.60N:Mg, cladding layers while a 25nm GaN:Mg is employed as a p-contact cap layer. We also report on the use of InGaN:Mg p-type layers to reduce the resistance of the p-contact layer in UV LED structures. Due to the lower acceptor ionization energy and lower work function, InGaN:Mg promises or offer better p-layer current spreading and lower contact resistance compared to GaN:Mg. The results of a study of the growth of InGaN:Mg along with Ohmic contact characteristics is described for application to UV-LED structures.

SESSION E2: Growth
Chairs: Martin Albrecht and Akihiko Yoshikawa
Monday Afternoon, November 29, 2004
Back Bay C (Sheraton)

1:30 PM *E2.1
Growth of Nonpolar GaN(1100) Films and Heterostructures by Plasma-Assisted Molecular Beam Epitaxy. Oliver Brandt, Yue Jun Sun and Klaus H. Ploog; Paul-Drude-Institut fuer Festkoerperelektronik, Berlin, Berlin, Germany.

Group-III nitrides are inherently piezo- and pyroelectric materials due to their wurtzite structure. Since the singular polar axis in the wurtzite lattice is the [0001] direction (the c-axis), large electrostatic fields may arise in heterostructures grown along this orientation. However, any direction perpendicular to [0001], such as [1100] (M-plane) and [1120] (A-plane), is free of both piezo- and pyroelectric polarization. The resulting absence of electrostatic fields along these directions constitutes a distinct advantage for fabricating high-efficiency GaN-based LEDs over corresponding [0001]-oriented structures on conventional substrates such as Al2O3(0001) and SiC(0001). Additionally, since the c-axis of GaN lies in the growth plane for the nonpolar directions, the optical properties of these structures are inherently strongly anisotropic, making them promising candidates for polarization-sensitive photodetectors. In this paper, we discuss the growth of M-plane GaN films and (In,Ga)N/GaN multiple quantum well (MQW) structures on LiAlO2(100) substrates by plasma-assisted molecular beam epitaxy. We first show that pure M-plane GaN films are obtained preferentially on a particular face of the substrate, which can be identified by a simple chemical treatment. Immediate Ga-rich nucleation is found to be required for the growth of pure M-plane GaN films. Layers nucleated at low temperature exhibit the highest structural and morphological quality reported so far for non-[0001]-oriented structures. Next, we report on the adsorption and desorption kinetics of Ga on M-plane GaN using in situ reflection high-energy electron diffraction (RHEED). Two stable surface phases are identified at lower temperature, which manifest itself by a (1x2) reconstruction at bilayer coverage and a (4x4) reconstruction at trilayer coverage. At growth temperature, Ga adsorbs layer-by-layer up to bilayer coverage after which Ga cluster and eventually droplet formation occurs. The bilayer desorption is delayed by "feeding" from this excess Ga. The optimum growth conditions with regard to surface morphology are those giving rise to trilayer coverage. Finally, we investigate the compositional profile of M-plane (In,Ga)N/GaN MQWs grown under the conditions identified to yield the smoothest surfaces. The results demonstrate that significant In surface segregation occurs for the case of M-plane (In,Ga)N. The dependence of the transition energies of the M-plane MQWs on the actual well thickness reveals, however, that the structures are indeed free of electrostatic fields along the growth direction.

2:00 PM E2.2
On the dynamics of InGaN dot formation by RF-MBE growth. Tomohiro Yamaguchi, Sven Einfeldt, Stephan Figge, Carsten Kruse, Claudia Roder and Detlef Hommel; Inst. of Solid State Physics, Univ. of Bremen, Bremen, Germany.

The growth of self-assembled InGaN quantum dots (QDs) has been widely investigated in recent years. Still there are many open fundamental questions concerning ideal growth routines and growth conditions. This includes issues like the role of growth interruptions. A deeper understanding of the underlying growth mechanism is important to establish a reliable InGaN QD growth. In this paper, the epitaxial growth of InGaN dots on GaN has been investigated with special focus on the dynamics of the dot formation and the dot stability. The variation of the growth temperature and the growth rate as well as the application of growth interruptions enabled us to propose a metastable 2D growth regime of InGaN on GaN. InGaN dots were grown at 400-570°C by molecular beam epitaxy (MBE) on GaN previously deposited by metal-organic vapor-phase epitaxy (MOVPE) on sapphire (0001) substrates. For relatively high growth temperatures over 500°C and relatively low growth rate less than 0.09 ML/s, large islands with a diameter of a few hundred nanometers were observed in addition to smaller dots having a diameter of a few ten nanometers. The density of the large islands and the small dots is in the order of 10^8 cm^{-2} and 10^{10} cm^{-2}, respectively. *In − situ* measurements of the morphology and the a-axis lattice parameter using reflection high-energy electron diffraction (RHEED) show three different subsequent growth regimes for InGaN on GaN. First, a 2D wetting layer grows coherently on the GaN. Second, the 2D growth proceeds with a slow lattice relaxation of the strained InGaN. Third, 3D growth sets in with a fast lattice relaxation towards unstrained InGaN. Considering the critical thickness for the 2D-3D transition reported in literature [1,2], the second regime is suggested to be a metastable state. The existence of a metastable 2D regime has been also reported for the case of CdSe QDs grown on ZnSe [3] and CdTe QDs grown on ZnTe [4]. In addition, the large islands appeared during the metastable 2D growth regime, while the small dots were formed only after the 2D-3D transition during the third step of the RHEED observation. When InGaN dots were grown either at a lower growth temperature around 450°C or with a higher growth rate of approximately 0.2 ML/s, the period of metastable 2D growth became shorter and the formation of large islands was suppressed. Detailed investigations on the impact of growth interruptions on the morphology of InGaN will be also presented to illustrate the metastability. [1] N. Grandjean et al: Appl. Phys. Lett. 72 (1998) 1078. [2] C. Adelmann et al: phys. stat. sol. (a) 176 (1999) 639. [3] K. Arai et al: J. Cryst. Growth 214/215 (2000) 703. [4] K. Godo et al: J. Appl. Phys. 92 (2002) 5490.

2:15 PM E2.3
How do InGaN Quantum Dots Form During MOVPE Growth? Sven Einfeldt, Tomohiro Yamaguchi, Claudia Roder, Andreas Tausendfreund, Stephan Figge and Detlef Hommel; Institute of Solid State Physics, University of Bremen, Bremen, Germany.

A large variety of growth regimes has been used to obtain InGaN quantum dots (QDs) or nano-islands on GaN via metalorganic vapor phase epitaxy (MOVPE). Although the formation of a wetting layer before the onset of QD growth was reported it remains unclear whether the QD formation process is goverend mainly by a reduction of the total energy of the system or whether growth kinetics has to be considered as well. This paper is aimed to distinguish between the two by studying the impact of energy relevant parameters such as strain on the one hand and dynamic parameters such as growth time and surface diffusivity on the other hand. InGaN was grown on thick GaN (0001) layers using atmospheric pressure MOVPE. For growth temperatures above 760°C where the indium mole fraction remains below 0.2, the InGaN exhibits a two-dimensional spiral growth mode. Moreover, indium droplets form on the surface when a critical InGaN layer thickness of about 4 nm is exceeded. When the growth temperature is below 780°C the indium content of InGaN is higher, and QDs with a density up to 10^{11} cm^{-2} and a height down to 10 nm can be found. While the size distribution of the QDs narrows with

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 InGaN 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 average indium mole fraction 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. Tao Xu[1], Adrian Williams[1], Theodore D. Moustakas[1], Lin Zhou[2] and David J. Smith[2]; [1]ECE, Boston University, Boston, Massachusetts; [2]Physics and Astronomy and Center for Solid State Science, Arizona State University, Tempe, Arizona.

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 by plasma-assisted molecular beam epitaxy. GaN QDs were formed by Stranski-Krastanow 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 step structure associated with the miscut of substrate 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 ripening 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 GaN QDs are currently 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[1], Stacia Keller[1], Benjamin A. Haskell[2], Feng Wu[2], Patrick Waltereit[2], Salka Keller[1], James S. Speck[2], Steven P. DenBaars[2,1], Shuji Nakamura[2] and Umesh K. Mishra[1]; [1]ECE, University of California, Santa Barbara, Santa Barbara, California; [2]Materials 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. Growth of nonpolar III-nitride 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 grown reduced-defect LEO a-plane GaN templates, MOCVD grown planar a-plane GaN templates, and MOCVD grown planar c-plane GaN templates. Effects of growth conditions, viz. 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 width on the luminescence properties were also investigated. The optimum barrier width of 11.5 nm for the a-plane MWQs 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.

3:30 PM *E2.6
Status of Bulk AlN Crystal Growth and Substrate Preparation: the Native Nitride Alternative.
Leo J. Schowalter[1,2], Jon B. Whitlock[1], Ken E. Morgan[1], Sandra B. Schujman[1], Keith R. Evans[1] and Glen A. Slack[1]; [1]Crystal IS, Inc., Watervliet, New York; [2]Rensselaer Polytechnic Institute, Troy, New York.

Native aluminum nitride (AlN) is a promising substrate material for emerging wide-bandgap electronic and opto-electronic devices. Although AlN crystal growth and substrate preparation technology is less mature than for sapphire and silicon carbide, substantial progress has recently been made using a sublimation-recondensation approach which overcomes the issues of high Al reactivity and the difficulty of incorporating N_2 molecules. Single crystal boules exceeding 25 mm in diameter and several cm in length have been grown and native-nitride substrates with very low average densities of dislocations (1000 cm^{-2}) have been prepared from these boules. X-ray topography of the substrates reveals dislocation-free regions exceeding several millimeter in size. Our partners have demonstrated that our native AlN substrates are superior to all other currently available substrates for mid-UV emitting applications (250 to 340nm). Performance modeling by other groups suggests that AlN substrates may ultimately surpass silicon carbide in performance for high power RF devices. Advantages include the same crystal structure as GaN, close lattice match to high Al-content nitride alloys, and a thermal conductivity exceeding 3 W/cm-K at room temperature. In addition, AlN and GaN have closely matched thermal expansions over typical growth temperatures. The AlN has a band-gap energy of 6.2 eV with an index of refraction of 2.2, which is attractive for the extraction of UV light. The AlN substrates are also highly insulating ($>10^{12}$ Ω-cm at room temperature and $>10^{8}$ Ω-cm measured at temperatures up to 500 °C) which is attractive for many high frequency devices. Crystal IS is currently developing 50mm diameter single-crystal boules. Structural characterization, current state-of-the-art, and key issues regarding the growth of bulk AlN crystals using the sublimation growth technique will be presented. *Partial support from DARPA and MDA is acknowledged.

4:00 PM E2.7
Growth and Characterization of Ammomothermal GaN Crystals Grown on HVPE Templates. Michael J. Callahan[1], Kelly Rakes[1], David Bliss[1] and Buguo Wang[2]; [1]SNHC, Air Force Research Lab, Hanscom AFB, Massachusetts; [2]Solid State Scientific, Nashua, New Hampshire.

Gallium Nitride bulk crystals greater than 1 cm^2 surface area and up to 1mm thick were grown on hydride vapor phase epitaxy (HVPE) seeds by the ammonothermal method. Ammonothermal growth is the analog of industrial hydrothermal quartz growth substituting high pressure aqueous solvents typically used in hydrothermal growth with alkaline or acidic supercritical ammonia. Growth rates on HVPE seeds approached 50 μm/day with 90% of the transported material nucleating on the walls of the autoclave. The nitrogen (C^-) face and gallium (C^+) face showed pronounced differences in impurity incorporation, photoluminescence (Pl), and structure. The nitrogen face incorporated fewer impurities and had reduced visible emission than the gallium face but was darker in appearance. Morphology and structural quality of the ammonothermal crystals varied depending on growth conditions. SEM, AFM and white synchrotron X-ray topography of various samples will be presented. Efforts to lower impurity incorporation, improved structural quality, and increase growth rates will be shown'. Finally, system scale up for production of 25 mm and greater free standing GaN substrates will be discussed.

4:15 PM E2.8
Ammonothermal Growth of GaN Utilizing Negative Temperature Dependence of Solubility in Basic Ammonia.
Tadao Hashimoto, Kenji Fujito, Feng Wu, Benjamin A. Haskell, Paul T. Fini, James S. Speck and Shuji Nakamura; ERATO/JST UCSB group, Santa Barbara, California.

Recently bulk GaN growth has been an intensively researched area because GaN wafers sliced from bulk crystals will have tremendous benefits for GaN-based devices. Most attempts to obtain bulk GaN are based on a gallium melt, however, growth from a gallium melt usually yields crystals with a platelet shape due to very limited solubility of nitrogen in gallium. Ammonothermal growth, which is categorized as solution growth in a supercritical fluid, is a promising candidate for bulk GaN growth owing to its predicted high solubility of source materials and fast transport of dissolved species. In addition, scalablility of ammonothermal growth is a potential advantage over other bulk growth methods. Several groups have reported evidence of GaN growth in supercritical ammonia, however, detailed reports on a solubility and characterization of grown crystals

are very limited. In this paper, we will report on a solubility study of GaN in a supercritical ammonobasic solution and characterization of GaN grown on free-standing GaN seeds. Solubility of GaN in supercritical ammonia was studied in a temperature range from 400C to 600C 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 had a negative dependence on temperature. Based on this result, we configured 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 single crystal fragments derived from HVPE growth and laser lift-off were used as seeds. The thickness of the seeds increased about 8.8 micron after three days of growth. The Ga face gained 5 microns and the N face gained 3.8 microns. Both sides of the seed showed band-edge emission in cathodeluminescence 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 a blue-shift on the N face. The Ga face was covered with pits and facets, whereas the N face was featureless. The surface roughness measured by AFM was 0.55nm for smooth regions of the Ga face and 2.06nm for the N face.

4:30 PM E2.9
Metalorganic Chemical Vapor Deposition of Non-polar III-Nitride Films over A-plane SiC Substrates. Jiawei Li, Zheng Gong, Changqing Chen, Adivarahan Vinod, Mikhail Gaevski, Edmundas Kuokstis, Maxim Shatalov, Ying Gao, Zehong Zhang, Arul Arjunan, T. S. Sudarshan, Jinwei Yang and M. Asif Khan; Department of Electrical Engineering, University of South Carolina, Columbia, South Carolina.

Wurzite III-nitride films grown in non-polar orientations such as (11-20) or (1-100) are very attractive for light emitting devices since the multiple quantum wells on non-polar faces do not suffer the quantum-confined Stark effect, which severely reduces the emission efficiency in polar (0001) orientation. Also, high electron mobility transistors on non-polar plane are especially interesting because of the possibility to modulate the sheet carrier density by doping. However, current non-polar nitride films have high densities of basal plane stacking faults and threading dislocations, which deteriorate the performance of non-polar devices. In this paper we will report the progress in growing non-polar A-plane nitride films and 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) AlN layer with RMS roughness of 0.3nm was obtained. From the results of XRD, the structural defects in the AlN layer on SiC substrates were 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 below 0.6nm. 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 at zero temperature 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 interactions with the Mg-vacancy complex 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. This work was partially supported by 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.

SESSION E3: Poster Session
Chairs: Bernard Gil and Christian Wetzel
Monday Evening, November 29, 2004
8:00 PM
Exhibition Hall D (Hynes)

E3.1
Sublimation Growth of Aluminum Nitride–Silicon Carbide Alloy Crystals on SiC (0001) Substrates. Zheng Gu[1], James H. Edgar[1], Edward A. Payzant[2], Harry M. Meyer[2], Larry R. Walker[2], R. Liu[3], A. Sarua[4] and Martin Kuball[4]; [1]Department of Chemical Engineering, Kansas State University, Manhattan, Kansas; [2]High Temperature Materials Laboratory, Oak Ridge National Laboratory, Oak Ridge, Tennessee; [3]Department of Physics and Astronomy, Arizona State University, Tempe, Arizona; [4]H.H. Wills Physics Laboratory, University of Bristol, Bristol, United Kingdom.

AlN–SiC alloys, with outstanding physical and electronic properties, are excellent for bandgap engineering and promising as substrates superior to either AlN or SiC. Thick (up to 1000 μm) AlN–SiC alloy crystals were grown on off–axis Si–face 6H–SiC (0001) substrate by the sublimation–recondensation method from a mixture of AlN and SiC powders at 1860–1990 °C in a N_2 atmosphere. The color of the crystals changed from transparent to dark green with increasing growth temperature. Raman spectroscopy, x–ray diffraction (XRD) and transmission electron microscopy (TEM) confirmed an AlN–SiC alloy was formed with the wurtzite structure and good homogeneity. Three broad peaks were detected in the Raman spectra, with two related to AlN–like and the third to SiC–like modes, all shifted relative to their usual positions in the binary compounds. Scanning Auger microanalysis (SAM) and electron probe microanalysis (EPMA) demonstrated the alloy crystals had an approximate composition of $(AlN)_{0.75}(SiC)_{0.25}$ with a stoichiometric ratio of Al:N and Si:C. The substrate misorientation ensured a two–dimensional growth mode confirmed by scanning electron microscopy (SEM). The dislocation density was lower than 10^6 cm^{-2} at the alloy surface, more than two orders of magnitude decreased in comparison with the density in regions close to the crystal/substrate interface, as determined by TEM.

E3.2
Determination of Surface Barrier Height and Surface State Density in GaN Film Grown on Sapphire Substrate. Seong Eun Park[1], Joseph J. Kopanski[1], Youn-Seon Kang[2], Lawrence H. Robins[2] and Hyun-Keel Shin[3]; [1]Semiconductor Electronics Division, National Institute of Standards and Technology, Gaithersburg, Maryland; [2]Ceramic Division, National Institute of Standards and Technology, Gaithersburg, Maryland; [3]Gwangju Techno Park, LED/LD Packaging Service Center, 958-3 Daechon-dong, Buk-gu, Gwangju 500-706, South Korea.

Photorelectance spectroscopy (PR) was performed to investigate the surface properties of GaN films grown on sapphire substrates. A surface barrier height and surface state density could be determined from the PR intensity as a function of the pump beam power density. From the period of Franz-Keldysh oscillations, the surface electrical field in the space charge region of GaN was calculated to be (197.3±11.4) kV/cm, resulting in the surface state density of $9.7\times10^{11}$$cm^{-2}$ and the surface barrier height of 0.64 eV. Furthermore, a surface barrier height of 0.66 eV was obtained from the fitting parameters.

E3.3
Excess Carrier Lifetime Measurements for GaN on Sapphire Substrates with Various Doping Concentrations and Surface Conditions by the Microwave Photoconductivity Decay Method. Masashi Kato, Hideki Watanabe, Masaya Ichimura and Eisuke Arai; Dept. of Electrical & Computer Eng., Nagoya Inst. of Tech., Naogya, Japan.

GaN has attracted interest as not only an optoelectronic device material but also a high power and high frequency electronic device material. For an electronic device material, excess carrier recombination in the material is the important characteristic and surface conditions of GaN are known to have influence on excess carrier recombination. 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 c-face sapphire 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 inductivity 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

harmonic Nd:YAG laser (λ=266 nm) and 10 GHz microwave were employed as excitation light and probe microwave, respectively, were performed to these samples. In order to confirm surface compositions, 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 are above 100 μs. The as-grown undoped 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 longer, 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 dominant for the n-type sample than for the undoped samples, the hole trap concentration is thought to increase with Si doping. 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 slow component. The ICP and RIE etching were performed to a thickness of 0.3 μm for n-type GaN, and the photoconductivity 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. Rohit Khanna[1], C.J. Kao[2], Ivan Kravchenko[4], F. Ren[3], G. C. Chi[2] and Stephen Pearton[1]; [1]MSE, University of Florida, Gainesville, Florida; [2]Electrical Engineering, National Central University, Chung-Li, Taiwan; [3]Chemical Engineering, University of Florida, Gainesville, Florida; [4]Physics, 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/Al/Pt/Au Ohmic contacts will not have adequate thermal stability.We have investigated chromium boride,tungsten boride and titanium boride contacts deposited by rf sputering for use on HEMT structures.These materials have thermal conductivities in the range 26-80 Watts per meter per degree Kelvin and eelctrical resistivities in the range 4-19 micro Ohm per centimeter.We have fond that the as-deposited contacts are always rectifying with poor ideality factors due to the presence of sputter damage,but that the ideality factors improve with annealing.We will present detailed electrical and chemcial 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. Yadong Wang[1], Tripathy Sudhiranjan[2], Soo Jin Chua[1,2] and Clifton G.Fonstad[1,3]; [1]Singapore-MIT Alliance, E4-04-10, 4 Engineering Drive 3, Singapore 117576, Singapore, Singapore; [2]Institute of Materials Research and Engineering, 3 Research Link, Singapore 117602, Singapore, Singapore; [3]Dept 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 nanostructures with high aspect ratio. In this study, GaN nanopillars were fabricated by inductively coupled plasma etching (ICP) using anodic aluminium 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 250-350 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 measurement where red shift of the E2(TO) mode from GaN nanopillars suggest partial relaxation of the compressive strain. 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. Martin[1], Sergi Hernandez[1], Paul R. Edwards[1], Ke Wang[1], Isabel Fernandez-Torrente[1], Masahito Kurouchi[2], Yasushi Nanishi[2] and Kevin P. O'Donnell[2]; [1]Physics Department, Strathclyde University, Glasgow, United Kingdom; [2]Department of Photonics, Ritsumeikan University, Shiga 525-8577, Japan.

Direct correlation of the composition and optical energies of relaxed InxGa1-xN has been the subject of many literature reports in the last decades, 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-poor ($x < 0.4$) samples grown by Metal-Organic Vapour Phase Epitaxy (MOVPE) [1] and there are also 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 InN-rich layers ($0.58 < x < 0.97$) in order to make comparison with sets of MOVPE and MBE InGaN epilayers with InN fractions up to 0.4 measured using identical techniques. We have employed electron probe microanalysis (EPMA) for the accurate measurement of the InN 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.Y. Davydov et al., phys. stat. sol. (b) 230, R4 (2002)

E3.7

Unusual properties of the red and green luminescence bands in Ga-rich GaN. Michael A. Reshchikov[1,2] and Hadis Morkoc[2,1]; [1]Physics, Virginia Commonwealth University, Richmond, Virginia; [2]Electrical Engineering, Virginia Commonwealth University, Richmond, Virginia.

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 highly resistive, and two other defect-related PL bands, namely a 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 Ga-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 for the RL band decreases by almost two orders of magnitude from 110 to 2 ms with increasing temperature 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. Reshchikov, 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.
Yahya Ibragimovich Alivov[1], Michael A. Reshchikov[1], Seydi Dogan[1], David Look[1], Vladimir Zinenko[1], Yurii Agafonov[1], Badavi M. Ataev[1], Valery Mamedov[1] and Hadis Morkoc[1]; [1]Electrical Engineering, VCU, Richmond, Virginia; [2]VCU, Richmond, Virginia; [3]Semiconductor Research Center, Wright State University, Dayton, Ohio; [4]Institute of Microelectronics Technology, Moscow, Russian Federation; [5]Institute of Physics, Daghestan 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 vein, we implanted N^+ in ZnO:Ga films grown by chemical vapor deposition using an ion energy of 180 keV and ion doses in the range from 10^{13} to 5×10^{13} cm^{-2}. The resistivity of the ZnO:Ga films increased with the implanted N^+ ion dose. We studied photoluminescence (PL) and cathodoluminescence from the N^+-implanted ZnO:Ga films as a function of temperature and excitation intensity. At low temperatures a 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 500°C, in contrast to the typical behavior of the irradiation-induced defect-related PL bands which 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. Andre Krtschil, Hartmut Witte, Armin Dadgar, Juergen Christen and Alois Krost; 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 different signals in the resulting spectra 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 substrates. They were electrically micro-characterized by temperature dependent and optically excited scanning surface potential microscopy (SSPM). These methods are modifications of the conventional SSPM technique based on AFM technique but are also sensitive to the local Fermi level position and the local carrier concentration. They provide information on the thermal activation as well as the optical transition energy of defects with submicron spatial resolution. These results were compared with DLTS, thermal and optical admittance spectroscopy as well as photoconductivity measurements evaluating the macroscopic deep level content. As an example, we analyzed the impact of inverted hexagonal pyramidal defects, which often appear in undoped GaN layers. In temperature dependent SSPM scans two donor states are found at the pyramid facets having thermal activation energies of about 100 meV and 300 meV, respectively, well known from DLTS and AS. Interestingly, in optically excited SSPM measurements we observed transitions due to these both donors randomly distributed within the non-disturbed GaN layer, but significantly enhanced in the pyramidal defects. This fact is interpreted as an accumulation of the related donor states around the inverted pyramids. The results for spatially resolved scans at pinholes and other types of structural defects as well as the impact of the layer doping on the defect parameters will be discussed in detail.

E3.10

Multiphoton Spectroscopy Studies of GaN/InGaN Layered Structures Grown on Sapphire. Matthew Gray[1], J. B. Schlager[1], N. A. Sanford[1], A. Munkholm[2] and M. R. Krames[2]; [1]Optoelectronics Division 815, National Institute of Standards and Technology, Boulder, Colorado; [2]Lumileds Lighting, San Jose, California.

Multiphoton spectroscopy performed with an ultrafast Ti:sapphire laser (λc 800 nm, 20 fs, peak intensity 15 TW/cm$\hat{2}$) is a convenient method of examining photoluminescence (PL) uniformity of GaN/InGaN layered structures grown on sapphire substrates. For n-photon PL to be observed (n is an integer >1) E(gap)/n < E(pump) < E(gap)/(n - 1) where E(pump) is the energy of the pump photon and E(gap) is the fundamental bandgap. Furthermore, the PL intensity derived from an n-photon process should scale as nth power of E(pump). We refer to this factor n as the pump power exponent (PPE). However it has been demonstrated that multiphoton PL (MPL) intensity in GaN which scales with non-integer PPE is suggestive of the presence of saturable midgap states [D. Kim, et al., PRB 55 (8), R4907 (1997)]. Therefore, MPL spectroscopy can serve the dual purpose of examining the spectroscopic uniformity of individual layers in a GaN/InGaN multilayer structure and also provide insight into the presence of midgap defect states. A number of MOCVD grown samples were examined: The first consisted of a sapphire substrate, nucleation layer, 3 μm of sublayer GaN, 3 nm thick InGaN quantum well (QW), and a 20 nm GaN cap. The room-temperature MPL of the QW peaked near 450 nm. The same layer sequence was used for the remainder of the samples but these had thicker InGaN layers, ranging from 300 to 400 nm, with In mole fractions in the range from 2-7%. The GaN sublayer in these samples was typically 1.5 μm in thickness and a 20 nm cap layer was used to terminate these structures as well. Room temperature confocal MPL studies of the samples were performed. In the QW sample the GaN MPL (emission at 366 nm) demonstrated a PPE=3.1 while the MPL from the QW (emission at 450 nm) yielded a PPE=2.9. For the thick InGaN sample with In mole fraction =6% we observe a PPE=3.6, and for In fraction =6.6% the PPE=3.4. In the MPL of a bulk free-standing HVPE grown GaN sample (emission at 360nm) we observe a PPE=3.0. Collection mode near-field scanning optical microscopy (NSOM) was used to map the MPL from the QW sample. Ultrafast excitation through the polished back surface of the substrate produced MPL from both the QW and the adjacent GaN. Room temperature NSOM mapping on a 30 x 30 μm region revealed large (>50%), uncorrelated intensity fluctuations (length scale <1 μm) in the respective MPL maps of the QW and the neighboring GaN layer. The spatial resolution of the NSOM tip was estimated to be 300 nm. For the pump wavelength used in these experiments we expected to see PPE=3.0 for emission from GaN (360 nm). The observation of non-integer PPE values for the InGaN layers (expect PPE=2 for QW and PPE=3 for thick layers) suggests the mediating role of defects, impurities, and/or phase separation in the multiphoton excitation process. Ongoing imaging work will provide more insight into the role of localized defects and inhomogeneities in non-linear spectroscopic studies of these materials.

E3.11

Reduction of dislocation density in AlGaN with high AlN molar fraction by using a rugged AlN epilayer. Akira Ishiga[1], Yuhuai Liu[2], Masaya Haraguchi[3], Noriyuki Kuwano[3], Hideto Miyake[1], Kazumasa Hiramatsu[1], Tomohiko Shibata[4] and Mitsuhiro Tanaka[4]; [1]Electrical and Electronic Engineering, Mie University, Tsu, Mie, Japan; [2]SVBL, Mie University, Tsu, Japan; [3]Interdisciplinary Graduate School of Engineering Sciences, Kyusyu University, Kasuga, Japan; [4]NGK Insulators, Ltd, Nagoya, Japan.

AlGaN alloys have been intensively researched for applications of light emitting diodes (LEDs), laser diodes (LDs) and photodetectors covering ultraviolet (UV) region because of their direct band gap energy from 3.4 eV to 6.2 eV. For deep UV LEDs and LDs, thick AlGaN with high AlN molar fraction is necessary for optical confinement and transparency. However, it is extremely difficult to grow thick AlGaN with high AlN molar fraction on GaN because of the AlGaN cracks under the large in-plane tensile stress. To solve this problem, we have used eptaxial AlN on sapphire as a substrate for the growth of AlGaN with AlN molar fraction of $0.2 < x < 0.8$. However, threading dislocation density of the AlGaN is over $10\hat{9}$cm$\hat{}$2. In this study, we have proposed the new approach of fabricating low dislocation density and high AlN molar fraction by using a rugged AlN epilayer on sapphire (0001). No crack is observed in the Al0.52Ga0.48N grown on the rugged epitaxial AlN layer. Cathodoluminescence image of wavelength distribution of AlGaN 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 Al0.52Ga0.48N layer was 8.8*$10\hat{7}$cm$\hat{}$2, which is two orders of magnitude less than that of AlGaN on flat AlN template.

E3.12

Fabrication and Characterization of UV Schottky Detectors by using a Freestanding GaN Substrate. Yasuhiro Shibata[1], Atsushi Motogaito[1], Hideto Miyake[1], Kazumasa Hiramatsu[1], Youichiro Ohuchi[2], Hiroaki Okagawa[2], Kazuyuki Tadatomo[2], Tatsushi Nomura[3], Yutaka Hamamura[3] and Kazutoshi Fukui[4]; [1]Electrical and Engineering, Mie University, Tsu, Japan; [2]Photonics Laboratory, Mitsubishi Cable Industries,Ltd., Itami, Japan; [3]Core Technology Center, Nikon Corporation, Sagamihara, Japan; [4]Research Center for Far-Infrared Region, Fukui University, Fukui, Japan.

We report that GaN substrate is more effective than sapphire substrate for detector. It is because that the dark current density of GaN Ultraviolet (UV) detector on 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, which will be available to a stepper with an excimer laser such as F2 laser and so on. The GaN and the AlGaN Schottky detector on a sapphire substrate have been fabricated and characterized. However, because of large dark current, good responsivity spectra under large reverse bias could not be obtained. In order to reduce dark current, we fabricated the GaN UV detectors by using a freestanding GaN substrate with low dislocation density. In this paper, GaN based UV Schottky detector on a freestanding GaN substrate was fabricated and characterized. i-GaN layer and n-GaN layer are grown on the freestanding GaN substrate by MOVPE. The transparent Ni/Au Schottky electrode is formed on i-GaN layer. As shown in results of I-V characteristics, the dark current density is less than 1 nA/cm-2 at 8V reverse bias, which is about 3 orders of magnitude lower than that of a detector on a sapphire substrate. From this result, it is found that the drastic reduction of dark current is realized by using GaN freestanding substrates.

E3.13

Strain-Induced Effects on the Resonant Tunneling of Holes in Zinc-Blende AlyGa1-yN/AlxGa1-xN/AlyGa1-yN Heterostructures. Meguenni Chahrazade, Zitouni Karima, Mokdad Nawal and Kadri Abderrahmane; Department of Physics, LEMOP-University Of Oran(Algeria), Oran, Algeria.

AlGaN based III-V multilayered heterostructures have recently attracted considerable attention due to their prospects in various device applications including high frequency, resonant tunneling diodes. In this work, we present a theoretical study of the effects of built-in strain due to the lattice mismatch on the mixing of resonant holes, on their tunneling transmission and on their tunneling current in Zinc-Blende AlyGa1-yN/AlxGa1-xN/AlyGa1-yN Double Barrier Heterostructures as a function of Al contents in the well (x varying from 0 to 0.15) and Al contents in the barriers (y varying from 0.2 to 0.3) for various geometry parameters : barrier (Lb) and well (Lz) widths values. The cubic structure is preferred here due to the absence of built-in polarization electric fields with respect to the corresponding hexagonal structure. Our calculations are performed within a multiband effective mass approch where anisotropy and mixing of the valence subband states are taken into account through a 6x6 Luttinger-Kohn Hamiltonian including the interactions between light hole (LH), heavy hole (HH), and spin-orbite (LS) split-off subbands. The elastic strain effects are included through the Pikus-Bir elastic Hamiltonian model, and the resonant tunneling of holes is described by the transfer-matrix technique. In the whole composition x and y ranges, the quantum well is always under biaxial compression with complicated and simultaneous nonparabolicity and strain-induced mixing effects contributions from all the three bands: LH, HH and LS. In order to distinguish the effects of nonparabolicity from those due to strain, we first perform the calculations by treating the holes in the parabolic approximation. Then the results are compared to those obtained from the complete nonparabolic model.In this way, we show that the LS splitt-off subband is only about 20meV from the top of the valence band and is thus very close in energy with respect to both of the HH and the LH subbands. This results in a strong nonparabolicity and mixing contributions coming from the interaction between this LS subband with both of the HH and the LH subbands, respectively. Moreover, This effect is shown to decrease with decreasing x, i.e. with increasing biaxial compression,and is minimum at x=0 in an AlyGa1-yN/GaN/ AlyGa1-yN heterostructure .

E3.14

Mesh Patterned Reflectors for High Extraction-Efficiency GaN-Based Light-Emitting Diodes. Hyunsoo Kim, Jaehee Cho, Jeong Wook Lee, Sukho Yoon, Hyungkun Kim, Cheolsoo Sone and Yongjo Park; Photonics Lab, Samsung Advanced Institute of Technology, Yongin-Si, South Korea.

Mesh patterned p-type reflectors were investigated for high efficiency GaN-based light-emitting diodes (LEDs) with flip-chip configuration. This mesh patterned reflector consists of the closed and opened region acting as an Ohmic contact layer and a reflective layer, respectively. A Pd/Ag scheme was used to make Ohmic contact at the closed region and the Ag single layer was used to reflect the generated light at the opened region. The coverage ratios of the closed area to opened area were 0, 0.44, 0.56, 0.78, and 1.25. It was clearly shown that the light output of LEDs gradually increased as the coverage ratio decreased with slight deterioration of a turn-on voltage measured at 20 mA. Based on this behavior, it was possible to optimize the Pd thickness and the coverage ratio for high reflectance and stable electrical operation of LEDs. In addition, a SiO2 layer was also inserted into Ag layer at the opened region to make higher reflectance. More detailed experimental and simulation results will be discribed and discussed.

E3.15

Investigation of Pit Formation Induced by the Desorption of InxGa1-xN Layer Grown by Metal-Organic Chemical Vapor Deposition. Tan Sakong, Hosun Paek, Joongkon Son, Sung-Nam Lee, Wonseok Lee, Okhyun Nam and Yongjo Park; Photonics Lab, Samsung Advanced Institute of Technology, Suwon, Gyeonggi-Do, South Korea.

Pit formation mechanisms in InGaN/GaN QWs have been reported in several literatures. It has been discussed that pits related to V-defects were mostly induced by threading dislocations(TD) and formed during the growth of InGaN QWs with 20% or higher In composition in order to relax the strain. To investigate pit formation mechanism, Two kinds of samples have been prepared, InGaN MQWs and InGaN bulks, and two samples per each. InGaN MQWs are consisted of five periods of In0.08Ga0.92N wells with 4nm thickness and In0.01Ga0.99N barriers with 10nm thickness, and InGaN bulks are 100nm thickness and 1% In composition. Two types of thermal treatment were employed in MOCVD reactor. One was to cool down just after sample growth(C.D.), and the other was to introduce in-situ thermal annealing(TA) at 1050°C for 60s after sample growth. Regarding to the treatments, NH3 and N2 ambient gases were supplied but group III sources were not. Through high resolution transmission electron microscopy (HRTEM) and atomic-force microscopy (AFM) analysis, pits related to V-defects were observed in the samples with C.D. The size was about 68nm diameter and 57nm depth. However, V-defects had not been observed in the samples with in-situ thermal annealing both in QW and Bulk. Specially, for QW with TA, we observed the full structures of QW even at the position of TD, which can not be explained by the previous model of defect formation. It is believed that V-defects have not been developed during the growth for stain relaxation, but only generated by desorption during cooling-down procedure after epitaxial growth. It is also suggested that TA can protect InGaN layer from desorbing and V-defects forming.

E3.16

Excitation Wavelength Dependent Raman Scattering in Low and Highly Degenerate InN Films. Vaman M. Naik[1], H. Dai[2], D. Haddad[3], R. Naik[2], J. S. Thakur[3], Gregory W. Auner[3], H. Lu[4] and W. J. Schaff[4]; [1]Natural Sciences, U Michigan-Dearborn, Dearborn, Michigan; [2]Department of Physics and Astronomy, Wayne State University, Detroit, Michigan; [3]Department of Electrical and Computer Engineering, Wayne State University, Detroit, Michigan; [4]Department of Electrical and Computer Engineering, Cornell University, Ithaca, New York.

The Raman spectra of low and highly degenerate InN films grown by conventional Molecular Beam Epitaxy (MBE) and Plasma Source Molecular Beam Epitaxy (PSMBE) have been studied using visible (514.5 nm) and near infrared (785 nm) excitation wavelengths. The MBE grown InN films have a low electron carrier concentration, $n_e < 1.0\text{x}10^{19}$ cm^{-3}, exhibiting an optical bandgap absorption edge of 0.6 to 0.7 eV. On the other hand PSMBE grown InN samples are highly degenerate with $n_e > 3\text{x}10^{20}$ cm^{-3} with an observed optical bandgap ranging from 1.5 to 1.9 eV. Raman spectra of low degenerate InN films show sharp E_2 and A_1(LO) modes whereas spectra of highly degenerate InN films show rather broad features indicating the presence of a large number of structural defects. In the latter samples a resonance enhanced Raman scattering is observed especially with 785 nm excitation energy. Another interesting observation is that the expected coupled plasmon LO-phonon modes are not detected in these films, rather a phonon mode is observed at the location of the unscreened A1(LO) mode. The observation of unscreened LO-phonon, and the absence of coupled plasmon LO-phonon modes have been attributed to Landau damping of the higher energy mode and coupling of the lower energy mode with the electron-hole pair excitations leading to the emergence of a mode very close to the A_1(LO).

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 use of silicon substrates for GaN based device structures is attractive for many reasons, particularly in terms of cost and scale, but there are also inherent drawbacks. In addition to the large lattice mismatch between silicon and GaN, which causes a high dislocation density, there is a particularly large thermal expansion coefficient mismatch between the two materials. This introduces tensile stress, on cooling from the growth temperature of around 1000°C, and can result in wafer bowing and cracking of the GaN. Using guidance provided by XRD, AFM and TEM analysis, MOCVD growth schemes incorporating the use of AlN nucleation layers on silicon have been used to grow GaN epilayers in a 6x2″ Thomas Swan CCS reactor. On these layers, structures have been grown incorporating various AlN, AlGaN and SiN interlayers, and the effects of both of these on the strain and dislocation density of GaN grown afterwards has been studied. Using these we have grown GaN films on Si which have an AFM roughness down to 0.11nm, with pit density of $4\text{x}10^8 cm^{-2}$, and have XRD rocking curve FWHM of 500 and 550 arcsec for the (002) and (101) reflections respectively.

E3.18

Effect of $[V_{Ga}\text{-}O_N]^{2-}$ 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.

Threading dislocation lines in epitaxial GaN act as electron acceptor sites with energy levels approximately 2.2-2.3 eV below the conduction band. These electrically active acceptors reduce the free carrier concentration, and thus both the electron mobility, by scattering, and the intensity of bandgap luminescence. However, the acceptor sites are not generally fully filled by electrons. The filling fraction of dislocation sites is a function of temperature, carrier concentration, dislocation density, as well as the basic structure of the epitaxial GaN. A combined $[V_{Ga}\text{-}O_N]^{2-}$ edge threading dislocation

has been proposed as the electrically active acceptor model. In this study, the fraction of filled traps and the mobility due to $[V_{Ga}\text{-}O_N]^{2-}$ edge threading dislocations in epitaxial GaN is numerically investigated by minimizing total energy of the charged dislocation; the predicted mobility is compared with available experimental data. Furthermore, the two different models of scattering potentials proposed by Read and by Bonch-Bruevich and Glasko are compared. The dislocation contribution to the drift and Hall mobility is calculated using these two electrostatic potentials with averaging over energy. Finally, the mobility effects of ionized impurities and the underlying lattice are combined with the dislocation contribution using Matthiesen's rule; results compare well with experimental data.

E3.19

Electrical Characterization of As- and [As+Si]-Doped GaN Grown by Metalorganic Chemical Vapor Deposition.

Mo Ahoujja[1], Said Elhamri[1], Rex Berney[1], Yung Kee Yeo[2] and Robert Hengehold[2]; [1]Physics, University of Dayton, Dayton, Ohio; [2]ENP, Air Force Institute of Technology, WPAFB, Ohio.

Isoelectronic 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 recombination that involves an As antisite deep level defect (AsGa). In spite of the promising application of As doped GaN in optoelectronic devices, very little electrical studies have been reported. In this study, electrical properties of arsenic and silicon-doped GaN films grown on sapphire substrates by low temperature metalorganic chemical vapor deposition have been investigated using temperature dependent Hall-effect and deep level transient spectroscopy (DLTS) measurements. The Hall data measured from the GaN layers shows that the concentration decreases with arsine flow (4, 40, and 400 sccm) at all temperatures, whereas, in general, the mobility increases for temperatures below 300 K. The carrier concentration of the Si-doped GaN, on the other hand, increases with the incorporation of arsine flow. This indicates that arsine flow enhances somehow the efficiency of Si doping in GaN. The mobility, however, decreases with the incorporation of arsine in Si doped GaN at all temperatures. The DLTS measurements show a deep level at around 0.7 eV below the conduction. We believe this level corresponds to the 0.766 eV deep level seen in As-implanted GaN films reported elsewhere and is therefore attributed to arsenic antisite.

E3.20

Polarity Control of GaN Thin Films Grown by Metalorganic Chemical Vapor Deposition on (0001) Sapphire.

Seiji Mita, Ramon Collazo, Raoul Schlesser and Zlatko Sitar; Dept. of Materials Science and Engineering, North Carolina State University, Raleigh, North Carolina.

The polarity control of GaN films grown on c-plane sapphire substrates by low pressure metalorganic chemical vapor deposition was achieved. GaN films grown directly on sapphire were found to have Ga-polarity (+c), while GaN films grown on nitrided substrates exhibited N-polarity (−c). The polarity of GaN films grown on low-temperature AlN buffer layers was governed by the buffer layer thickness and the subsequent annealing time. Properly annealed AlN buffer layers resulted in growth of Ga-polar films, while under- or over-annealed buffer layers yielded GaN films with mixed polarity. The growth process was optimized to yield smooth films (better than 1 nm RMS roughness) of either polarity. Wet chemical etching in an aqueous solution of KOH was used to determine the polarity type. This solution attacked even smooth N-polar GaN films, whereas Ga-polar films remained completely unaffected, even by long (120 min) dips in a 4 M KOH solution. In Ga-polar films grown without an AlN buffer layer, the etch solution attacked the interface between the substrate and GaN epilayer rather than the epilayer surface and, as a result, the GaN epilayer lifted-off. This indicated that Ga-polar GaN films grown directly on sapphire possess a higher interfacial defect density than Ga-polar films grown on the AlN buffer layers. In addition, N-polar films were electrically conducting with n-type carrier concentrations on the order of 10^{18} cm^{-3}, while Ga-polar films were insulating (R_{sheet} >20 MΩ/sq). Experimental details and characterization results of polarity-controlled GaN films will be presented.

E3.21

High Field Magneto-transport Studies of (Ga,Mn)As Dilute Magnetic Semiconductors.

Kartik C. Ghosh[1], T. Kehl[1], Md. Arif[1], S. Mishra[2] and J. Broerman[1]; [1]Physics, Astronomy and Materials Science, Southwest Missouri State University, Springfield, Missouri; [2]Department of Physics, University of Memphis, Memphis, Tennessee.

Dilute magnetic semiconductor (DMS) has a wide range of potential application in spintronic devices. DMS Ga1-xMnxAs, in which the exchange interaction is mediated by carrier, is widely studied system both theoretically and experimentally. The ferromagnetism in this system is very sensitive with concentration of Mn ion as well as disorder. Several groups have studied annealing effects on magnetic and transport properties of Ga1-xMnxAs 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 (Ga,Mn)As DMS with lower (1.5%) Mn concentration. We choose the lower doping level of Mn, because it provides to study a wide range of temperature in both ferromagnetic and normal region. Thin films of (Ga, Mn)As have been grown on semi-insulating chromium oxide doped GaAs (001) substrates by low temperature molecular beam Epitaxy. X-ray diffraction measurements reveal that the crystal structure of the homogeneous GaMnAs film is zinc-blend. The Raman spectra from the films also confirm this phase of GaAs. 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 compare to annealed sample. However, well above the ferromagnetic transition temperature as 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 could be due to presence 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.

E3.22

Dependence of the E_2 and A_1(LO) Modes on InN Fraction in InGaN Epilayers.

S. Hernandez[1], R. Cusco[2], L. Artus[2], K. P. O'Donnell[1], R. W. Martin[1], I. M. Watson[3], M. Jurouchi[4] and Y. Nanishi[4]; [1]Department of Physics, University of Strathclyde, Glasgow, Scotland, United Kingdom; [2]Institut Jaume Almera, Consejo Superior de Investigaciones Cientificas (C.S.I.C.), Barcelona, Spain; [3]Institute of Photonics, University of Strathclyde, Glasgow, Scotland, United Kingdom; [4]Department of Photonics, School of Science and Engineering, Ritsumeikan University, Shiga, Japan.

InGaN ternary alloys have been extensively studied for their potential optoelectronic applications. By varying the InN fraction, it is possible to tune the energy emission from the ultraviolet to near infrared [1]. Despite the interest of these compounds as light emitters, the growth of these alloys is still a challenge because of the large difference in interatomic spacing between InN and GaN (≈ 11%). In a common anion alloy, the cation distribution results in modifications in the distance between atoms which affect the vibrational properties. Raman scattering is a suitable technique to investigate the influence of the In content on the crystallinity of the alloy through the study of its vibrational properties. We present here a Raman study of InGaN epilayers with high and low Indium content. To avoid luminescence background in the InGaN Raman spectra, the Ar^+ laser line λ = 514.5 nm was used as a Raman excitation source for the samples with high In content, whereas the He-Cd laser line λ = 325 nm was used for low In concentration layers. The Raman spectra show the E_2 and A_1(LO) optical phonons of the InGaN samples. The frequency of both modes decreases linearly with the InN fraction. There is a broadening of these modes for moderate compositions and the linewidth decreases at both ends of the composition range, as a consequence of reduced cation disorder. We have also observed a mode between the E_2 and A_1(LO) modes which exhibits a frequency decreasing almost linearly with InN fraction. This mode may be related to disorder activated optical modes due to the intrinsic alloy disorder which relaxes the momentum-conservation selection rule. Our results show a one-mode behaviour for both E_2 and A_1(LO) modes of InGaN. This result agrees with the mode behaviour previously reported in InGaN with lower InN content [2]. [1] J. Wu, W. Walukiewicz, K. M. Yu, J. W. Ager III, E. E. Haller, H. Lu, and W. J. Schaff, Appl. Phys. Lett. 80, 4741 (2002). [2] M. R. Correia, S. Pereira, E. Pereira, J. Frandon, and E. Alves, Appl. Phys. Lett. 83, 4761 (2003).

E3.23
Growth of Gallium Nitride via Iodine Vapor Phase Epitaxy.
William J. Mecouch, Zach Reitmeier, Ji-Soo Park, Brian P. Wagner, Robert F. Davis and Zlatko Sitar; Materials Science and Engineering, North Carolina State University, Raleigh, North Carolina.

Thick layers of gallium nitride have been deposited on 1μm thick MOVPE GaN(0001) thin film substrates using a novel vertical iodine vapor phase epitaxy system. The system featured three concentric flow zones that separate the reactant gasses until they reach the substrate. Nitrogen flowing through the innermost zone delivered iodine vapor from an external bubbler to the molten Ga (kept at 1000°C) and GaI 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 GaI 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 1mm at their base). Lower Ga supersaturation, 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 Chhajed[1], E. F. Schubert[1,2], Thomas Gessmann[1], Y. L. Li[1] and Yangang Xi[2]; [1]Department of Electrical, Computer, and Systems Engineering, Rensselaer Polytechnic Institute, Troy, New York; [2]Department 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 color rendering indices (CRIs) 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 øC to 80 øC. 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 this illumination source unsuitable for certain application. 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 dopes more efficiently at low growth temperatures due 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-assisted 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 indium flux in 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 (800C) under group III rich conditions. This result is consistent with our p-type studies of GaN. We also found that the electrical and surface morphology of the films depends strongly on the Mg flux. Specifically, we found the resistivity is minimum when the Mg cell temperature is between 350C to 360C and it increases at lower and higher Mg cell temperatures. The sample with the lowest resistivity has carrier concentrations between 1-3x1017cm-3, corresponding mobilities 3-1cm2/v.s. The films grown under optimal Mg temperatures have smooth surface morphology, while those grown under high Mg flux show evidence of inversion domain boundaries. Correspondingly, the cathodoluminescense 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, Tzer-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 muliquantum 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 in a closed He cryostat. At room temperature, 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 EL intensity can be analyzed by rate equation model. Based upon the experimental observations, excitation cross section (σex), de-excitation cross section (σde), carrier lifetime (τ), radiative recombination lifetime (τrad) and nonradiative recombination lifetime (τnrad) are obtained to corroborate the heterobarrier enhancement effect. The different rigorous 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×E-11 cm2 and σde=2.77×E-11 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. These quantities reveal that 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 depending on temperature can 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.
Hyungjin Bang[1], Junji Sawahata[3], Takahiro Maruyama[1,2], Shigeya Naritsuka[1,2] and Katsuhiro Akimoto[3]; [1]21st Century COE program, Meijo University, Nagoya, Aichi, Japan; [2]Department of materials science and engineering, Meijo University, Nagoya, Aichi, Japan; [3]Institute 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 hardly affected by temperature variation. Among RE dopants, Eu seems to be most interesting element in GaN since it shows red luminescence (622nm) which is relatively hard to get by 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 Eu^{3+} ion. The red luminescence was analyzed to be generated through trap-level-related energy transfer from host GaN, and the external emission efficiency was estimated to be about 0.18 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 thin films were grown on sapphire (0001) substrates by gas-source molecular beam epitaxy (GSMEB) using uncracked NH_3 gas with 6N purity as nitrogen source. Metallic Ga with 6N purity and Eu with 3N purity were evaporated from conventional Knudsen effusion cells. The growth temperature of Eu-doped GaN was 700°C and Eu doping concentrations were controlled by varying Eu cell temperatures from 390 to 500°C. Eu concentration in GaN was estimated by Rutherford back scattering (RBS) spectrometry. From the PL measurement, sharp emission peaks around 622nm were observed for all Eu doped samples, and those peaks can be assigned as intra atomic $^5D_0$-$^7F_2$ transition of Eu^{3+}ion. Host luminescence starts to be suppressed by Eu doping and completely quenched on Eu 3 at.% (Eu cell temp. 460°C) doped sample. PL intensity t 622nm versus various Eu concentrations were studied. The intensity showd 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 profiles measured by theta-2theta method, although 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 16 at.% Eu doped sample and the EuN formation may be responsible to the luminescence quenching.

E3.29
Abstract Withdrawn

E3.30
Extended X-Ray Absorption Fine Structure Studies of InGaN Epilayers. Viatcheslav Katchkanov[1,2], K. P. O'Donnell[1], S. Hernandez[1], R. W. Martin[1], J.F.W. Mosselmans[2], Y. Nanishi[3] and M. Kurouchi[3]; [1]Department of Physics, Strathclyde University, Glasgow, Scotland, United Kingdom; [2]Synchrotron Radiation Department, CCLRC Daresbury Laboratory, Warington, England, United Kingdom; [3]Department 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 of InGaN luminescence is due to formation of In-rich InGaN clusters i.e. //accidental //quantum dots (QDs) [2]. In the case of formation of //accidental// QDs 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 Molecular Beam Epitaxy (MBE) with InN fraction ranging from 20% to 96% 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 distances were found to be longer than in case of 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 Azuhata, T. Sota, and S. Nakamura, 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. Viatcheslav Katchkanov[1,2], K.P. O'Donnell[1], S. Hernandez[1], J.F.W. Mosselmans[2] and N.R.J. Poolton[2]; [1]Department of Physics, Strathclyde University, Glasgow, Scotland, United Kingdom; [2]Synchrotron Radiation Department, CCLRC Daresbury Laboratory, Warrington, England, United Kingdom.

Conventional X-ray Absorption Fine Structure (XAFS) analysis is a powerful technique to obtain information about local structure in the neighbourhood of atoms in a solid targeted 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 //majority//sites. Optical luminescence may also be emitted after excitation of core-levels by X-rays [2]. Since the structural environment of an emitting centre determines its fluorescence, using X-ray Excited Optical Luminescence (XEOL) for the collection of XAFS data may provide site specific information about optically active 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 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 MOCVD.
Sunwoon Kim[1], Jeong Tak Oh[1], Kyu Han Lee[1], Dong Joon Kim[1], Je Won Kim[1], Yong Chun Kim[1] and Jeong Wook Lee[2]; [1]Semiconductor Device R&D Group, Samsung Electro-Mechanics, Suwon, Gyunggi-Do, South Korea; [2]Photonics Lab, Samsung Advanced Institute of Technology, Suwon, Gyunggi-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 epilayer from sapphire substrate to mirror coated Si or GaAs wafer; patterning the sapphire substrate to suppress the total internal reflection. In this study, we investigated the growth 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 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 rugged surface like a corrugated interface substrate. As reactor pressure was reduced, the rugged surface became flattened. The optical power of flip chip LED with patterned substrate was 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. Keyan Zang[1], Soo Jin Chua[1,2], Lian Shan Wang[2] and Carl V. Thompson[1,3]; [1]Singapore-MIT Alliance, Singapore, Singapore; [2]Institute of Materials Research & Engineering, Singapore, Singapore; [3]Department of Materials Science and Engineering, MIT, Boston, Massachusetts.

The periodic silicon delta-doping technique was employed during metalorganic chemical vapor deposition of epitaxial GaN on AlN buffer layers grown on Si(111). Periodic silicon delta doping during growth of both the AlN and GaN layers led to growth of GaN films with decreased tensile stresses and decreased threading dislocation 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. Yiyi Wang[1], Anirban Bhattacharyya[2], Ahmet S. Ozcan[1], Theodore D. Moustakas[2], Karl F. Ludwig[1], Lin Zhou[3] and David Smith[3]; [1]Physics Department, Boston University, Boston, Massachusetts; [2]Electrical and Computer Engineering, Boston University, Boston, Massachusetts; [3]Department 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. Superlattice 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 performed 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 particular possible arrangements of these three layers that could explain the experimental results. While it has previously [1] been conjectured that the miscut of the sapphire substrate affects the ordering of the films [2], our studies find no correlation between miscut and ordering. [1] E. Iliopoulos, K.F. Ludwig Jr., T.D. Moustakas, Journal of Physics and Chemistry of Solids 64, 1525 (2003). [2] P. Venezuela, J. Tersoff, J.A. Floro, E. Chason, D.M. Follstaedt, F. Liu, M.G. Lagally, Nature 397, 678 (1999).

E3.35

Mechanism of Metalorganic MBE Growth of High Quality AlN on Si (111). Iulian Gherasoiu, Sergey Nikishin, Gela Kipshidze, Boris Borisov, Anilkumar Chandolu, Mark Holtz and Henryk Temkin; Electrical Engineering, Texas Tech University, Lubbock, Texas.

AlN 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 AlN on Si (111) using trimethylaluminum and ammonia as sources of aluminum and nitrogen, respectively. Metalorganic 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 material quality. We demonstrate very efficient growth, with the growth rate in excess of 0.5 μm/h and low ammonia consumption of less than 1 sccm. Over the entire domain of growth parameters, the surface roughness remained in the range from 12 to 53 $\AA$ rms for AlN layers up to 1000 nm thick. Here, the low values of the roughness are associated to the low growth temperature (760 ^{0}C), behavior that contrasts with that usually observed in gas source MBE with elemental Al source. X-ray diffraction linewidth as narrow as 141 arcsec has been demonstrated for samples grown under stoichiometric conditions. High temperature of the ammonia injector promotes the transition to the two-dimensional growth, while reducing the growth rate, pointing out the importance of surface hydrogen. We demonstrate that hydrogen plays an important role in the MOMBE process acting as a surfactant and passivating surface nitrogen bonds.

E3.36

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

High quality AlN single crystals grown by physical vapor transport and by powder sublimation were investigated optically by means of Raman, photoluminescence (PL), photoconductivity (PC), and absorption spectroscopy. The AlN single crystals were grown under different experimental conditions varying temperature, pressure, precursors, and crucible material in order to analyze and optimize the crystalline structure and quality of AlN bulk material. The absorption edges of the AlN 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 2.5 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 monochromatic and polychromatic transmission and by band-to-band excitation. The high transparency in the visible and NIR spectral range reveals the absence of transition metal ions. FIR transmission measurements were performed to analyze the Reststrahlen bands 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 Efficiency of GaInN LEDs by Omni-Directional Diffuse Reflectors. Jong Kyu Kim[1], Hong Luo[2], Jay M. Shah[1], Yangang Xi[2], Thomas Gessmann[1] and E. Fred Schubert[1,2]; [1]ECSE, Rensselaer Polytechnic Institute, Troy, New York; [2]Department of Physics, Applied Physics, and Astronomy, Rensselaer Polytechnic Institute, Troy, New York.

Enhancement of light extraction in GaInN light-emitting diodes (LEDs) employing diffuse reflectors rather than specular ones is presented. The diffuse reflector consists of a SiO2 layer roughened by the chemically assisted ion beam etching (CAIBE) and an Ag layer on a roughened surface. The reflector is integrated into GaInN LEDs. The GaInN LED structure was grown by metal-organic chemical vapor deposition on c-plane sapphire substrate. LED mesa structures are obtained by the CAIBE. Ti/Al/Ni/Au ohmic contacts to n-GaN are deposited and annealed at 600 oC under N2 ambient. Then, Ru (5 nm) is deposited on p-GaN and annealed at 500 oC 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 polystyrene nano-spheres are randomly distributed by spin coating and used as etching mask for CAIBE. Then, an array of circular micro-contacts is patterned 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 reflection depends on 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

Discrete Steps in the Capacitance Voltage Characteristics of GaInN/GaN Light Emitting Diode Structures. Yong Xia[1,3], Eric Williams[1,3], Yena Park[2,3], Ibrahim Yilmaz[1,3], Jay M. Shah[2,3], E. F. Schubert[2,3,1] and C. Wetzel[1,3]; [1]Department of Physics, Applied Physics and Astronomy, Rensselaer Polytechnic Institute, Troy, New York; [2]Department of Electrical, Computer, and Systems Engineering, Rensselaer Polytechnic Institute, Troy, New York; [3]Future Chips Constellation, Rensselaer Polytechnic Institute, Troy, New York.

A detailed modeling of the electronic bandstructure of GaInN alloys and GaInN/GaN heterostructures typically used for high efficiency light emitting diodes is of high relevance for future improvements. 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 GaInN/GaN LED-type heterostructures under 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 its dependence on the emission wavelength of the LED-type structure. We anticipate that this analysis will be most useful in the assessment of the reproducibility and homogeneity of each individual quantum well within an LED structure. The authors wish to thank Steven Kurtz for initial experiments on the subject.

E3.39

Optimization of p-type AlGaN/GaN and InGaN/GaN Superlattice Design for Enhanced Vertical Transport. M.Z. Kauser[2,1], A. Osinsky[1], Jianwei Dong[1], B. Hertog[1], A. Dabiran[1] and P.P. Chow[1]; [1]SVT Associates, Eden Prairie, Minnesota; [2]ECE, University of Minnesota, Minneapolis, Minnesota.

One of the challenges in III-N research is to achieve highly conductive p-type layers needed for vertical transport devices such as HBTs, LEDs and Laser Diodes. Enhancement of lateral free hole conductivity has been demonstrated in modulation doped AlGaN/GaN superlattice structures [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 [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 suggests 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 2D sheet free hole concentration increases about 1.5 times for the optimized structures. For the optimized p-type AlGaN/GaN superlattice structure a barrier height of 150meV and a sheet hole density of 1x1013 cm-2 per period has been achieved. The modulation doping scheme, which 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 sheet resistance in p-type InGaN/GaN 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 more then 4 times. The free sheet hole concentration increases 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 promise for further reduction of series resistance and improved the thermal management in advanced III-Nitride vertical transport devices. The authors would like to thank Dr. Colin Wood of ONR for valuable discussion and encouragement regarding this work. This research was partially supported by NSF contract # DMI-0319870, monitored Dr. Winslow L. Sargeant. References: [1] A. Y. Polyakov, N. B. Smirnov, A. V. Govorkov, A. V. Osinsky, P. E. Norris, S. J. Pearton, J. van Hove, A. Wowchak and P. Chow, Appl. Phys. Lett. 79, 4372 (2001). [2] S. Heikman, S. Keller, D. S. Green, S. P. DenBaars and U.K. Mishra, J. Appl. Phys. 94, 5321(2003). [3] K. Kumakura, T. Makimoto and N. Kobayashi, Proceedings of International Workshop on Nitride Semiconductors, IWN2000, TA3-3 (2000).

E3.40

Influence of Mis-Orientation of C-plane Sapphire Substrate on the Early Stages of MOCVD Growth of GaN Thin Films. Seongwoo Kim[1], Hideo Aida[2] and Toshimasa Suzuki[1]; [1]System Engineering, Nippon Institute of Technology, Saitama, Japan; [2]NAMIKI Precision Jewel Co. Ltd., Tokyo, Japan.

Elucidation of the growth mechanism of group-III nitride thin films is very important to obtain device quality epitaxial layers to develop highly efficient high frequency, high power/temperature electronic devices. We reported the effect of mis-orientation angle of c-plane sapphire substrate on surface morphology and crystal quality of 3μm-thick GaN thin films grown by metalorganic chemical vapor deposition (MOCVD) [1]. The mis-orientation angle toward (10-10) direction of c-plane sapphire substrate was changed within the range of 0.00-1.00 degree. With the atomic force microscopy (AFM) observation, it was found that the smoothest surface of GaN film was obtained on 0.15° mis-oriented substrate and the surface roughness was increased with both increasing and decreasing of mis-orientation angle. On the other hand, the full width at half maximum (FWHM) of both GaN (002) and GaN (201) reflections was slightly improved as mis-orientation angle increased. These results point out that the mis-orientation angle of sapphire substrate strongly affects on the growth mechanism of MOCVD grown GaN thin films. In this study, we have observed the early stages of the epitaxial growth of GaN thin films to elucidate the growth mechanism of them grown by MOCVD on mis-oriented sapphire substrates. Undoped GaN thin films were grown at 1035 °C in an EMCORE D-125 multi-wafer MOCVD system. Thirty nm thick GaN layers grown at 510 °C were used as nucleation layers (NLs). The reactor pressure was fixed at 200 Torr throughout the study. The film growth was interrupted at early stages, and then the film was quenched to room temperature and took out from the reactor. First, we observed the morphologies of rather narrow area (20 μm x 20μm) surfaces by AFM. It was found that the larger the mis-orientation angle was, the larger the grains became. This result agrees with the x-ray diffraction (XRD) result, i.e. the larger the grain size was, the lower the density of threading dislocations (TDs) became, reducing the FWHMs of x-ray rocking curve (XRC). Then, we observed the wider area (70μm x 70 μm)by scanning laser microscopy (SLM). SLM images showed not only the similar tendency to AFM results but also the differences of the early stages of the step flow growth mode. [1] Seong-woo Kim, Hideo Aida and Toshimasa Suzuki, Ext. Abst. of The 5th Int. Symp. on Blue Laser and Light Emitting Diodes, Gyeongju, 2004, pp.356.

E3.41

Thermally stable transparent Ru-Si-O Schottky contacts for n-type GaN and AlxGa1-xN. Eliana Kaminska[1], Anna Piotrowska[1], Krystyna Golaszewska[1], Andrian Kuchuk[1], Radoslaw Lukasiewicz[1], Emil Kowalczyk[1], Adam Barcz[1,2], Elzbieta Dynowska[2], Rafal Jakiela[2], Anna Stonert[3], Artur Szczesny[1], Andrzej Turos[3] and Michal Wiatroszak[1]; [1]Institute of Electron Technology, Warsaw, Poland; [2]Institute of Physics PAS, Warsaw, Poland; [3]Soltan Institute for Nuclear Studies, Warsaw, Poland.

Reliable Schottky contacts to GaN-based devices should use metallisation that is highly conductive, stable in contact with GaN, and capable to withstand treatments at elevated temperatures during device processing and further operation. Targeting high temperature applications we have chosen to study the properties of ruthenium based metallisations: elemental Ru, RuO_2 and Ru-Si-O. Both Ru and RuO_2 are high melting point materials, characterised by low bulk resistivity and work function exceeding 5 eV. The feasibility of conducting, amorphous ternary Ru-Si-O material has been recently reported by Gasser et al. [1]. If thermally stable, the amorphous microstructure would be the most effective in preventing interfacial reactions in the contact region. We have developed the deposition and processing of amorphous, conducting Ru-Si-O films, and studied the electrical characteristics and thermal reliability of Ru-based contacts on n- type GaN as well as on AlGaN/GaN heterostructure. Ru, RuO_2 and Ru-Si-O layers were deposited by reactive magnetron sputtering in DC mode, using either Ru or RuSi target, in a mixture of Ar and O_2. Heat treatments were done at 400-1000^{0}C in either N_2 or O_2 flow. The electrical characterisation involved I-V and C-V measurements. Ti/Al ohmic contacts were prepared for this study. The microstructure of as-deposited and annealed contacts was analysed by high-resolution XRD, SIMS and RBS. Optical properties of films were measured by photospectrometry. Crucial point during the deposition was to optimise the O_2/Ar ratio and the working pressure with regard to the film conductivity and stress. The resistivity of 50 nm thick Ru, RuO_2 and Ru-Si-O films was 2x10-5 Ωcm, 3x10-4 Ωcm and 1x10-2 Ωcm, respectively. Ru films were highly textured, RuO_2 - nanocrystalline while Ru-Si-O - amorphous. RuO_2 films were highly stressed and peeled off. In contrast, Ru and Ru-Si-O layers showed excellent adhesion to nitride substrates. All Ru-based metallisations formed Schottky barriers with n-GaN and AlxGa1-xN. Of these, Ru films yielded the lowest barrier heights. RuO_2 and Ru-Si-O barriers were similar, 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 2200nm. The transmittance of 50nm thick layer was 80%. The above properties make Ru-Si-O contact a very attractive candidate for gate metallisation in GaN-based HEMTs and UV detectors for high speed and high temperature operation. [1] S. M. Gasser, E. Kolawa, M. -A. Nicolet, J. Appl. Phys. 86, (1999) 1974. Work supported by the grant from the State Committee for Scientific Research 3 T11B 008 026.

E3.42

In-Situ Investigation of Surface Stoichiometry During GaN Growth by Plasma-assisted Molecular Beam Epitaxy using RHEED-TRAXS. Brenda VanMil, David Lederman and Thomas H. Myers; West Virginia University, Morgantown, West Virginia.

Reflection high-energy electron diffraction total-reflection-angle X-ray spectroscopy (RHEED-TRAXS) has been shown to be an effective tool for measuring chemical composition of a growing surface with sub-monolayer sensitivity for InGaAs/GaAs and YBaCuO films. In this technique, the high-energy electrons from the RHEED measurement also excite x-ray fluorescence. Since the RHEED electrons just penetrate the surface, and by using a geometry that measures x-ray takeoff at the total reflection angle, RHEED-TRAXS probes primarily the top 20 to 30 $\AA$ of material. Thus, the surface stoichiometry of layers of GaN and InGaN can be directly probed during growth, including direct measurement of the amount of adsorbed excess Ga or surface ratios of Ga to In. In addition, surface segregation effects of dopants, which can lead to near monolayer coverage in the case of Mg, should be directly measurable for the first time. Examples of planned investigations follow. High quality N-polar and Ga-polar GaN grown by MBE is grown under gallium stable conditions, which results in the formation of an excess gallium layer on the surface. There are several models of the amount of Ga in the excess layer. In addition, too much gallium incident on the surface during growth results in gallium droplet formation. Thus, RHEED-TRAX can be used to test predictions and also serve as an in-situ diagnostic to determine the optimal growth regime without forming droplets. There have been many indirect measurements indicating that near-monolayer coverage of Mg occurs during heavy doping for Ga-polar growth. Again, this model can be tested, and RHEED-TRAXS can be used as a diagnostic to work on techniques for altering surface segregation. This work was supported by AFOSR MURI F49620-03-1-0330.

E3.43

Probing the 2-dimensional electron gas in AlInGaN/ GaN heterostructure by photoluminescence spectroscopy. Chew Beng Soh[1,2], Soo Jin Chua[1,2], Wei Liu[2], Sudhiranjan Tripathy[2] and Dongzhi Chi[2]; [1]Electrical and Computer Engineering, National University of Singapore, Singapore, Singapore; [2]IMRE, Singapore, Singapore.

The optical transitions in unintentionally doped AlyInxGa1-x-yN under tensile strain with composition of (0.01< x< 0.02, 0.08< y<

0.14) 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 AlInGaN quaternary alloys. In our samples, we have clearly observed such effects from low-temperature PL spectroscopy for AlInGaN of epilayer thickness > 40 nm. To investigate the effect of piezoelectric field and Al composition on the optical transition of 2DEG formed at AlInGaN/ GaN interface, the ratio of integrated intensity of transition for the confined 2DEG and the AlInGaN band edge emission, I2DEG/IBE was studied. At low temperature, higher I2DEG/IBE is observed for thinner sample as there is less adsorption of emission from 2DEG due to the shorter transition distance as compared to thicker sample. With increasing temperature, thermal excitation comes into play leading to faster decline in I2DEG/ IBE for thinner sample. At higher temperature, I2DEG/ IBE is stronger in the thicker sample due to higher Al composition caused by composition pulling. The deeper well created by piezoelectric field formed in the thicker AlInGaN are 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 Schaff
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-MBE. Akihiko Yoshikawa, Yoshihiro Ishitani, Song-Bek Che, Ke Xu, Xinqiang Wang, Masayoshi Yoshitani, Wataru Terashima 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. After that, it is expected to develop super functionality photonic devices in the optical communication wavelengths by using InN-based III-nitrides, such as ultra high speed optical modulators based on ISBT device structure and/or light emitters including LEDs and LDs operating at higher temperatures than those of conventional light emitters available at present. Because of the very low dissociation temperature of InN, however, there are many problems/barriers to achieve the epitaxy control of InN and also to develop nano-processes to fabricate InN-based III-nitrides hetero-structures. Since the epitaxy temperature is as low as below 600°C, if In-droplets appear once on the growing surface, it becomes very difficult to continue the growth. Therefore only limited groups can grow thick epilayers at present. We have developed an RF-MBE system equipped with RHEED, spectroscopic ellipsometry, CAICISS, and UHV-AFM/STM etc. This MBE system was suitable to monitor and control precisely the surface stoichiometry and also to control very fine hetero-nanostructures based on InN. In this paper, it is reported that a) the growth and properties of thick (up to 10μm) N-polarity InN epilayers grown on (0001) sapphire by using our unique RF-MBE system, b) the fabrication and properties of InN/GaN SQW/MQW structures, and c) the growth and properties of InN quantum dots on GaN.

9:00 AM E4.2
Effects of the Nitridation Process of (0001) Sapphire on Crystalline Quality of InN Grown by RF-MBE. Daisuke Muto[1], Ryotaro Yoneda[1], Hiroyuki Naoi[2], Tsutomu Araki[1] and Yasushi Nanishi[1]; [1]Department of Photonics, Ritsumeikan University, Kusatsu, Shiga, Japan; [2]Center 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 crystalline quality of InN, due to formation of AlN on the surface of sapphire substrate [1]. However, the relationship between nitridation conditions and InN crystalline quality has not been investigated in detail. In this paper, we have systematically investigated the effects of nitridation process of the sapphire substrates on InN crystalline 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 process of the sapphire substrate prior to growth was carried out at 300-800°C for 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 nitrogen flux modulation for the first 10 min of the growth [2]. Then, the subsequent growth was carried out for 1 hour. XRD was used to examine the crystalline quality of InN. Higher temperature and longer time of nitridation of sapphire resulted in clearer patterns of AlN in the RHEED patterns. The InN epilayers grown after the nitridation process carried out at different temperatures of 300, 530 and 800°C for a fixed duration of 1 hour have exhibited different XRC-FWHM values of 3.21, 6.00 and 9.87 arcmin for the (002) InN reflection, and 110.5, 87.4 and 51.7 arcmin for the (102) InN reflection, respectively. When nitridation temperature was fixed at 800°C, different nitridation durations of 0.5, 1 and 2 hours have resulted in different XRC-FWHM values of 8.75, 9.87 and 11.21 arcmin for the (002) InN reflection, and 93.5, 51.7 and 36.5 for the (102) InN reflection, respectively. From these results, it was found that lower temperature or shorter time of nitridation process resulted in smaller tilt and larger twist distributions, respectively. We consider that the tilt distribution is related to the surface roughness of nitrided sapphire because the surface of sapphire gets rougher under stronger nitridation process. As for the twist distribution, on the other hand, we consider that it is related to the degree of the formation of AlN layer on the surface of sapphire, as we confirmed from the RHEED patterns of nitrided sapphire. [1] T. Yamaguchi et al., Mat. Res. Soc. Symp. Proc. **693** (2002) 195. [2] K. Balakrishnan et al., J. Cryst. Growth **189/190** (1998) 244.

9:15 AM E4.3
Growth of InN Films by Cluster Beam Epitaxy and RF Plasma-assisted MBE. Tai-Chou P. Chen, Christos Thomidis, Joshua Abell, Anirban Bhattacharyya and Theodore D. Moustakas; Electrical and Computer Engineering, Boston University, Boston, Massachusetts.

InN is much less investigated than GaN and AlN. Over the past two years, it has been shown that InN films grown by RF plasma MBE in single crystalline form have a relatively small energy gap (0.7eV), 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 photovoltaics. The most important issue for the growth of this material is the availability of high flux of active nitrogen to prevent the 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 adiabatic expansion from high stagnation pressure through a narrow nozzle. The clusters are ionized by a single positive charge through electron impact and accelerated up to approximately 20 to 25 KV prior to their disintegration on the substrate. Due to the high local temperature produced during the impact of clusters with the substrate, this method is suitable for the growth of InN at very low temperatures. Films have been grown by these methods at temperature between 300C and 550C using GaN template with the Ga or N polarity, in order to investigate InN films in its two polarities. We found that when the InN film are relative thick (1um), the InN film delaminates from the GaN upon exposure to the atmosphere, presumably due to the high lattice mismatch between GaN and InN (11%). The films are auto-doped n-type with carrier concentration higher than 1e19 cm-3 and electron mobilities of 100 cm2 /V.s. The optical absorption constant indicates a small energy gap. However, a plot of the square of the absorption constant versus photon energy is not a straight line, as expected for direct semiconductors, and thus we cannot accurately define a single energy gap from these measurements. This may partly due to band tailing caused by the heavy n-type doping.

9:30 AM E4.4
Study on RF-MBE growth and control of InN dots on N-polar GaN grown on vicinal c-plane sapphire. Naoki Hashimoto[1,2], Naohiro Kikukawa[1], Song-Bek Che[1,2], Yoshihiro Ishitani[1,2] and Akihiko Yoshikawa[1,2]; [1]Department of Electronics and Mechanical Engineering, Chiba University, Chiba, Japan; [2]InN-project as a CREST program of JST, Chiba University, Chiba, 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 in between InN and GaN is about 11 %, 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 on N-polarity GaN by radio frequency molecular beam epitaxy (RF-MBE) and systematically investigated the effects of growth time, growth temperature, and V/III beam flux ratio on the diameter, height, and density of InN dots. It is necessary and preferable to achieve atomically flat surface for the GaN underlying layer to carefully study the growth mechanism of InN quantum dots on it. Therefore we first tried to grow GaN layer with step flow-like flat surface by using vicinal sapphire (0001) substrate. We have already clarified that the growth temperature of N-polarity InN can be higher about 100°C than that of In-polarity, resulting in remarkable improvement of InN crystalline quality. Therefore we grew N-polarity GaN layer in order to grow N-polarity InN. For InN dots growth, the growth temperature was 500°C and growth rate was set at 0.21ML/s under both N-rich and In-rich conditions. Growth period was varied from 4 to 38 seconds (0.84ML − 8ML). InN dots growth process 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 higher temperature growth conditions. And we investigated how the diameter, height, and density of InN dots vary with total supply of InN. Less than 3.5ML 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 3.5ML 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 Yoshitani[1,3], Song-Bek Che[1,2,3], Yoshihiro Ishitani[1,2,3] and Akihiko Yoshikawa[1,2,3]; [1]Dept. of Electronics and Mechanial Engineering, Chiba Univ., Chiba, Japan; [2]VBL, Chiba Univ., Chiba, Japan; [3]InN-Project as a CREST program of JST, Chiba Univ., Chiba, Japan.

The stoichiometry control in RF-MBE of InN epitaxy was carried with 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 in InN 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 stoichiometory control. Generally, higher growth temperature is preferable to grow a film with high-quality and flat surface. In the case of InN, 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 epitaxial 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 epitaixal 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 570-590°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, $<\epsilon_1>$ and $<\epsilon_2>$ showed a convolute signal trace and gradually converged on the dielectric constants of InN in each wavelength. The values of the dielectric constants were estimated from a sample with the layer thickness of over 6μm and atomically flat surface. On the other hand, if the growth condition was out of the stochiometory, the trajectories deviated from the convolute signal trace as mentioned above. When the In accumulation occurred on the surface, both pseudo-dielectric functions changed sensitively and increased abnormally. Based on these results, we could investigate the property of the surface and adjust the V/III ratio to keep the stoichiometry condition of InN by means of in-situ SE monitoring.

10:30 AM *E4.6
Structural and optical properties of InN films and dots analysed by transmission electron microscopy. Thilo Remmele and Martin Albrecht; Characterisation, Institute for Crystal Growth, Berlin, Germany.

The discovery of low bandgap InN as well its predicted outstanding electrical properties (small effective mass, high mobility) has lead to renewed interest this material. The main challenge in understanding fundamental properties of InN is up to now the growth of high quality epitaxial InN films. Despite the progress in the last years thick epitaxial layers are characterised by residual tensile strain, dislocations, twist boundaries and small angle grain boundaries. For applications in devices growth of nanoscopic InN structures, e.g. islands is necessary. Due to the high mismatch og f=0.11 between InN and GaN islands with sizes in the 2 nm range have to be grown in controlled way. In the present talk we will address recent progress in characterisation of InN films and quantum structures based on transmission electron microscopy. We will present results on samples grown by both MBE and MOCVD. We address the dislocation formation mechanism and correlate directly optical and structural properties of InN structures by the use of cathodoluminescence in the transmission electron microscope.

11:00 AM E4.7
Influence of the MOVPE Growth Conditions on the Lateral Growth of InN onto Sapphire Substrates. Sandra Ruffenach, Olivier Briot, Benedicte Maleyre and Bernard Gil; GES, CNRS, Montpellier, France.

Indium Nitride is a very interesting material, since extremely good electrical properties have been theoretically predicted, both at low and high electric field. As a consequence, there is a strong potential for application in high frequency devices and terahertz applications. Surprisingly, the bandgap of InN is not yet clearly established, due to its extremely dificult growth. Recently, it has been established that the band gap value could be as low as 0.7 eV, making it very interesting for telecommunication applications, or could lie at higher energy, close to 1.2 eV, resulting in a strong potential for solar cell applications. However, the growth of InN is extremely complex, due to both a low dissociation temperature and the lack of appropriate substrate. In this paper, we report results for the MOVPE growth of InN on various substrates (GaN, AlN, Si, sapphire). We found that the best results are obtained on sapphire : mirror-like epilayers on two inches substrates, with a mobility of 900 cm2/V.s. However, the key to this result is to control the wetting of InN onto sapphire, i.e. controling the lateral growth at the initial growth stages. This can be realized by performing an optimized nitridation step before the InN growth phase, and by controling the ambient chemistry during growth. As a matter of fact, the wetting properties are partly determined by the ambient composition and pressure. We report here a detailed analysis by Atomic Force Microscopy (AFM) of the first stages of growth of InN, under various growth conditions (using N2 or He carrier gas, and different NH3 partial pressures) and we demonstrate that we can improve the substrate wetting to the point where the obtention of smooth, mirror-like layers can be reproducibly realized. This experimental work is further supported by a statistical thermodynamical analysis of the wetting angle versus growth ambient, and we observe a good agreement between the theoretical analysis and the experimental results.

11:15 AM E4.8
Mechanism of Raman Scattering in Doped InN. Claire Pinquier[1], Francois Demangeot[1], Jean Frandon[1], Olivier Briot[2], Benedicte Maleyre[2], Sandra Clur-Ruffenach[2] and Bernard Gil[2]; [1]Laboratoire de Physique des Solides, Universite Paul Sabatier, Toulouse, France; [2]Groupe d'Etudes des Semiconducteurs, Universite Montpellier II, Montpellier, France.

Raman spectra of non-intentionally doped InN films grown on sapphire by metal-organic vapour phase epitaxy have been recorded and carefully analysed, using various wavelengths and polarisation configurations. No significant variation of the LO phonon frequency is detected, even in the case of highly doped samples. Comparison of these experimental data with lineshape calculations for both excitations of the free electron gas and of the atomic vibrations reveals that that q wave-vector non-conserving mechanisms are at the origin of the Raman scattering by the LO phonon. The relaxation of q conservation law could be due to elastic scattering of photoexcited carriers by impurities rather than the absorption effect of the incident laser.

11:30 AM E4.9
Phonon Lifetimes and Decay Mechanisms in InN. James W. Pomeroy[1], Martin Kuball[1], Hai Lu[2] and William J. Schaff[2]; [1]H.H. Wills Physics Laboratory, University of Bristol, Bristol, United Kingdom; [2]Department of Electrical Engineering,

Cornell University, Ithaca, New York.

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 investigated. An important aspect is 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 A_1(LO) lifetime of $\approx$ 1 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 long considering the current contributions from defect/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 μm), reflecting the decreasing defect and impurity levels with increasing layer thickness. The temperature dependence of A_1(LO) lifetimes can be explained by a combination of asymmetric two phonon and symmetric three phonon decay channels. The A_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 E_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 E_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[1], S. Bin-Omran[1], L. Bellaiche[1] and Ahmad Alsaad[2]; [1]Physics Department, University of Arkansas, Fayetteville, Arkansas; [2]Department of Physical Sciences, 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 isostructural phase transition (which is a rather rare phenomenon) from first-principles calculations. Interestingy, 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 optic (TO) mode.

SESSION E5: Optical Properties
Chairs: Tomasz Dietl and Bernard Gil
Tuesday Afternoon, November 30, 2004
Back Bay C (Sheraton)

1:30 PM *E5.1
Recombination Dynamics in Low-Dimensional Nitride Systems. Yoichi Kawakami[1], Akio Kaneta[1], Kunimichi Omae[2], Masayoshi Abiko[1], Ruggero Micheletto[1], Giichi Marutsuki[3], Yukio Narukawa[3] and Takashi Mukai[3]; [1]Dept of Electronic Science and Engineering, Kyoto University, Kyoto, Japan; [2]Paul-Drude-Institut fur Festkorperelektronik, Berlin, Germany; [3]Nitride Semiconductor Research Laboratory, Nichia Corporation, Anan, Tokushima, Japan.

A number of reports have recently been appeared on the spatial mapping of luminescence in $In_xGa_{1-x}N$/GaN quantum wells by optical microscope, by cathodoluminescence (CL), or scanning near-field optical microscopy (SNOM). Although spatial resolution of optical microscope is typically a few to several hundreds nm that is restricted by diffraction limit, CL has a much smaller diameter in exciting electron beam (e-beam), However, the spatial resolution is generally much larger that the e-beam diameter not only because incident electrons spread during the penetration to the sample, but also because generated carriers/excitons diffuse spatially before recombining radiatively or non-radiatively. Another drawback of CL is that both active and cladding layers are photo-excited, while selective photo-excitation to active layers is achieved in 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 nm to 70 nm in a 3 nm-thick $In_xGa_{1-x}N$/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 modes. It was found that the probed area could 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 applicability to study on carrier/exciton dynamics where spatial and temporal dynamics have to be taken into account. Furthermore, blinking phenomena as well as photo-memory effects were observed in samples emitting at blue-green to green spectral range. The former is the simultaneous switching of PL intensity between bright state and dark state at local points with time scale of sub-second, and the latter is gradual increase or decrease of PL background intensity in accordance with continuous wave (CW) photo-excitation, both of which suggests the importance of trapped carriers on the oscillator strength of localized carriers/excitons. Our recent finding is that the location of the blinking can be controlled by the formation of sub-micron structured pillars by the dry etching technique, where trapping centers generated at etched side-walls contribute to this effect.

2:00 PM E5.2
Microscopic Luminescence Properties and Vertical Exciton Transport in InGaN/GaN Light Emitters on Si(111). Till Riemann, Juergen Christen, Karsten Fehse, Armin Dadgar and Alois Krost; 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 final device. Thus, typical issues of lateral contact geometries, e.g. mesa fabrication and inhomogeneous current spreading, are avoided. Additionally, in vertically contacted LEDs, electronic transport takes place parallel to the typical threading dislocation line direction, i.e. may completely occur inside the perfect material. However, crack-free growth of micrometer-thick nitrides on silicon demands for the insertion of AlN-interlayers which might act both as highly resistive regions and as non-radiative recombination centers, thus inhibiting vertical electronic transport. We investigate the vertical exciton diffusion and capture into the active region of InGaN / GaN light emitters on Si(111) by highly spatially and spectrally resolved cathodoluminescence (CL) microscopy. Enhanced exciton capture into the active InGaN / GaN multiple quantum well (MQW) from the surrounding material is imaged and quantitatively analysed. For contact-ready LEDs, the active region consists of an InGaN/GaN:Si MQW embedded between GaN:Si and AlGaN:Mg followed by GaN:Mg at the top. While cracking of the diode stack at a thickness above one micrometer is completely avoided by the multiple insertion of low-temperature AlN, effective reduction of the threading dislocation density is achieved by ultra-thin SiN interlayers. Using cross-sectional CL imaging we can unambiguously identify the light emissions from the individual LED components: In the n-GaN luminescence near 359nm (T=6K) the positions of LT-AlN interlayers are revealed by local drops of CL intensity at their vertical position. The emission of the typical p-GaN band around 400nm only occurs for direct local CL excitation. Here, no carrier diffusion in c-direction is observed, thus giving a direct measure of the spatial CL resolution. In contrast, strong InGaN MQW emission around 470nm 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 n-GaN 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 carrier 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.

2:15 PM E5.3
Microphotoluminescence studies of excitonic and multi-excitonic states of quantum dot-like localization centers in InGaN/GaN structures. K. Sebald, H. Lohmeyer, J. Gutowski, 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 exhibit 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-wells and analyze their properties. The samples are grown by metal-organic chemical vapor deposition on 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 nonresonantly at 3.82 eV. At low temperature (5 K) 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 single 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 band 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 saturates 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 it 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 quenching of luminescence 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. Hsiang-Chen Wang[1], Yen-Chen Lu[1], Chih-Chung Teng[1], Chih-Chung Yang[1], Kung-Jen Ma[2], Chang-Chi Pan[3] and Jen-Inn Chyi[3]; [1]Graduate Institute of Electro-Optical Engineering, National Taiwan University, Taipei, Taiwan; [2]Department of Mechanical Engineering, Chung Hua University, Taipei, Taiwan; [3]Department of Electrical Engineering, National Central University, Chung-LI, Taiwan.

Because of the large lattice mismatch between GaN and InN, two prominent phenomena in 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 efficiency improvement. 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, an 800-nm InGaN thin film with silicon doping of 5 x 1018 cm-3 in concentration was grown at 800 oC. 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 pump-probe experiments. From this value, the induced 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 lattice 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. Mitsuru Funato[1], Koji Nishizuka[1], Yoichi Kawakami[1], Yukio Narukawa[2] and Takashi Mukai[2]; [1]Department of Electronic Science and Engineering, Kyoto University, Kyoto, Japan; [2]Nitride Semiconductor Research Laboratory, Nichia Corporation, Tokushima, Japan.

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 variations of the electric field due to piezoelectric and spontaneous 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 difficult to grow polar materials such as GaN on non-polar substrates. On the other hand, there is no report on the growth and optical characterization of the 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 are 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 growth facets. The well thickness and In 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 energies of the (0001), {11.2}, and {11.0} QWs at RT were evaluated to be 2.22, 3.15, and 3.39 eV, respectively. With a micro PL measurement system, PL was separately observed from each MQW and the emission energy agreed reasonably well with the above calculation. More importantly, PL intensity of 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 as large as about 40% at RT. The radiative recombination lifetime of the {11.2} MQW was about 0.38 ns at 13 K, which was 3.8 times 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 electric 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.

3:30 PM E5.6
Investigation of Compositional Inhomogeneity in GaN and InGaN Alloys Using Near-Field Scanning Optical and Scanning Kelvin Probe Microscopies. Bing Han[1], Melville P. Ulmer[2] and Bruce W. Wessels[1]; [1]Department of Materials Science and Engineering and Materials Research Center, Northwestern University, Evanston, Illinois; [2]Department of Physics and Astronomy, Northwestern University, Evanston, Illinois.

Compositional fluctuation is universally observed in InGaN alloy due to the large atomic radii mismatch between Ga and In atoms. The inhomogeneous distribution of In (with the formation of In rich regions) is of critical importance in determining the luminescence efficiency and spectral response of InGaN based light emitting diodes, laser diodes, and detectors. Similarly in heavily Mg doped p-type GaN, the compositional fluctuation of Mg strongly affects the optical and electrical properties of GaN:Mg epilayers and devices. Despite their scientific and technological importance, details of the compositional fluctuations in InGaN and GaN:Mg are not well established. Conventional characterization techniques such as Secondary Ion Mass Spectrometry are limited by their spatial resolution and cannot be used to determine the nano-scale fluctuations. In this work, compositional fluctuation is studied by near field scanning optical microscopy (NSOM) and scanning Kelvin probe microscopy (SKPM) with nanometer resolution. From the NSOM images of InGaN, a microstructure characteristic of spinodal decomposition is observed in nominally single-phase epilayers as determined by X-ray diffraction, which is attributed to the phase separation of InGaN alloy. With increasing In concentration, the domain size of the microstructure increases from 150 nm to 3 μm, and the root mean square (RMS) fluctuation of the NSOM intensity in transmission also increases, which are attributed to increasing compositional fluctuation. At high In concentrations, the histograms of the NSOM intensity deviate from the Gaussian distribution, indicating the In is not randomly distributed. In the case of GaN:Mg,

domains with different local Mg concentrations are observed by NSOM and SKPM. For GaN:Mg with an average Mg concentration of 4×10^{19} cm^{-3}, large hexagonal pyramids are formed. The domain size 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 hexagonal pyramids by NSOM, which is attributed to the formation of Ga droplets at the terminating end of pure screw dislocations.

3:45 PM E5.7
Carbon-Related Deep States in Compensated n-Type and Semi-Insulating GaN:C and their Influence on Yellow Luminescence. Andrew Michael Armstrong[1], A. R. Arehart[1], C. Poblenz[2], D. S. Green[2], U. K. Mishra[3], J. S. Speck[2], D. C. Look[4] and S. A. Ringel[1]; [1]Electrical Engineering, The Ohio State University, Columbus, Ohio; [2]Materials Department, University of California, Santa Barbara, Santa Barbara, California; [3]Electrical & Computr Engineering Department, University of California, Santa Barbara, Santa Barbara, California; [4]Semiconductor Research Center, Wright State University, Dayton, Ohio.

Carbon doping of GaN is important for generating semi-insulating (SI) buffer layers for high performance AlGaN/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 as a function of conductivity since, traditionally, 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 GaN:C, but not for SI GaN:Fe, requires developing a full understanding of C-related deep states in SI GaN:C to achieve a comprehensive picture of YL in GaN. Here, motivated by the need to fully understand the mechanism of achieving SI behavior in GaN:C, coupled with the fundamental question of YL behavior in SI GaN material, we present the results of a systematic study of GaN:C 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 (DLOS) is used to surmount the thermal emission limitations 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. Comparison 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 compares favorably with the expected C_N acceptor that compensates background n-type GaN. The Ec-1.94 eV state is seen only in MBE-grown GaN:C and is reported for the first time. The Ec-2.54 state concentration strongly depends on C concentration and is greatest for SI GaN:C. Its location in the bandgap is consistent with that expected for YL processes, similar to models involving VGa deep states in n-GaN, and thus may be the source for YL in GaN:C. We are currently performing additional PL and EPR studies to directly observe PL bands and determine V_{Ga} concentration as a function of [C] and conductivity in these MBE- and MOCVD-grown samples. Direct correlations between C concentration, specific deep level concentration determined via our new methodology for trap studies in wide gap SI materials, V_{Ga} concentration and YL intensities, are expected to provide a picture of how C-related states achieve SI behavior and associate with YL in GaN:C for the first time.

4:00 PM E5.8
Near Field Optical Spectroscopy of GaN/AlN Quantum Dots. Arup Neogi[1], Hadis Morkoc[3], Brian P. Gorman[2], Atsushi Tackeuchi[4], Tadashi Kawazoe[5] and Motoichi Ohtsu[5]; [1]Physics, University of North Texas, Denton, Texas; [2]Material Science and Engineering, University of North Texas, Denton, Texas; [3]Physics and Electrical Engineering, Virginia Commonwealth University, Richmond, Virginia; [4]Applied Physics, Waseda University, Tokyo, Japan; [5]Electrical 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 depicts the interplay of in-built strain induced electric fields and quantum confinement in nitride based materials. When QD size is of the order of the exciton Bohr radius, the quantum confinement and built-in polarization field affects both the exciton binding energy and the optical bandgap and allow tailoring of the optical properties of the system. GaN QDs on AlN layers were grown on sapphire substrates by MBE. We have demonstrated size control of QDs by strain modification using various growth techniques to achieve emission energies ranging from 2.5 eV to 3.9 eV. In self-organized GaN QDs, the quantum confinement effect observed in the "classical" GaAs-based QD is offset by the large piezoelectric fields (5 MV/cm) resulting in a red-shift of the ground state optical transition below the bulk bandgap by about 0.5-1.2 eV. The built-in strain field along with size-control of GaN QDs can therefore be used to tune the emission wavelength of GaN-QD based optical emitters. Atomic force microscopy measurements show honeycomb structure of GaN QDs. High-resolution TEM images show a vertical correlation of the dots among the stacked layers with dot width 5-10 nm and height of 2-4 nm. The near-field photoluminescence (PL) has been measured to isolate the optical properties of a single QD from the ensemble effect. Using NSOM measurements, the PL line-width (FWHM) of a single or an ensemble of few QDs has been observed to be 1.55 meV. Comparatively in the far-field limit the FWHM exceeds 100 meV. Near-field PL also shows the size-distribution and the emission-energy dependence in stacked QDs. A strong emission from a single QD structure within 450 nm x 450 nm region is observed at 3.59 eV, which corresponds to monolayer fluctuations. There are larger numbers of dots luminescent at 3.49 eV and 3.61 eV and the emission intensity are relatively weaker than QDs emitting at 3.59 eV. The preferential emission characteristics of QDs at various energies are also related to the strain relaxation in the QD matrix. The emission mechanism is also investigated by time resolved PL spectroscopy. A comparison of the temperature dependent PL characteristics of stacked and unstacked QD structures has also been performed. In unstacked QDs non-radiative recombination process dominates the emission at higher temperature. In stacked QDs, vertical coupling reduces nonradiative processes as there is no significant difference in the decay constants due to change in temperature from 10 K to 100 K. Stacking results in higher emission efficiencies at 300 K. Signature of phonon-bottle neck phenomenon is also observed in unstacked single QD layers as evidenced by the long PL decay constant at 10 K.

4:15 PM E5.9
Recombination Mechanism in Short-Wavelength GaN/AlGaN Quantum Wells. Andreas Hangleiter, Daniel Fuhrmann, Thomas Retzlaff and Uwe Rossow; Institute of Technical Physics, Technical University of Braunschweig, Braunschweig, Germany.

So far, light emission by AlGaN-based heterostructures operating in the ultraviolet spectral region is far less efficient than visible light emission by their GaInN-based counterparts. It is frequently argued that localization by random potential fluctuations in GaInN-based structures makes them more efficient. On the other hand, recent detailed studies of GaInN/GaN quantum wells have led us to the conclusion that at room temperature carriers are mobile rather than localized in such structures. In order to study the effect in ultraviolet emitters, we have grown GaN/AlGaN quantum well structures on sapphire and SiC substrates using low-pressure MOVPE. A 1 micron thick buffer layer (GaN or AlGaN) on the substrate was used to ensure good material quality before a single or multiple GaN quantum well and an AlGaN cap layer were deposited. The emission wavelength of the QW's was varied in the 320-360 nm range by adjusting the QW width. Using temperature dependent photoluminescence measurements at variable excitation power we have determined the internal quantum efficiency (IQE) and analyzed its temperature and excitation power dependence 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 recombination. Compared to GaInN-based structures, the nonradiative lifetime at room temperature is much shorter.

4:30 PM E5.10
Oxygen-related Shallow Acceptor in GaN. Bo A. Monemar[1], Plamen Paskov[1], Filip Tuomisto[2], Kimmo Saarinen[2], Hiroshi Amano[3] and Isamu Akasaki[3]; [1]Dept of Physics and Measurement Technology, Linkoping University, Linkoping, Sweden; [2]Laboratory of Physics, Helsinki University of Technology, Helsinki, Finland; [3]Department 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 about 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 3.27 eV DAP 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 coexisting with the 3.27 eV DAP [3]. Various other suggestions have been made for the corresponding acceptor,

such as C [4] or Si [5] on N site. No convincing correlation of these suggested acceptors with corresponding doping experiments have been provided. In this work we demonstrate a definite positive correlation between the PL intensity of the 3.27 eV DAP emission with O doping, in MOCVD grown layers. The GaN layers were grown with addition of various amounts of H2O or CO2 in the vapour phase. The samples include a nominally undoped reference layer grown with pure NH3, in this case a very low O doping is expected. The VGa-O concentration is measured with positron annihilation techniques. The only reasonable expectation for an oxygen-related acceptor in GaN is the VGa-O complex. In the literature it is generally accepted that this double acceptor is related to the so called yellow luminescence (YL) peak at about 2.4 eV in GaN [6]. This peak is also weakly present in the O-doped MOCVD samples. The VGa-O complex is known to be stable over a large temperature range [7], while the acceptor related to the 3.27 eV DAP PL is unstable under electron irradiation in p-type material [8]. It is also unstable upon thermal annealing above 500 K. This indicates that the acceptor related to the 3.27 eV DAP in addition contains a loosely bound element, that is easily dissociated when the Fermi level is low in the bandgap. Data from positron annihilation as well as SIMS will be presented, in addition to the optical PL data. A model for the identity of the 3.27 eV acceptor will be given, and discussed in relation to the presently most popular identification of the 3.27 eV DAP as related to the Mg acceptor. [1]. R Dingle and M Ilegems, Solid State Commun 8, 1227 (1971) [2]. O Lagerstedt and B Monemar, J Appl Phys 45, 2266 (1974) [3]. H G Grimmeiss and B Monemar, J Appl Phys 41, 4054 (1970) [4]. S Fischer, C Wetzel, E E Haller and B K Meyer, Appl Phys Lett 67, 1298 (1995) [5]. E R Glaser, et al, Phys Rev B 68, 195201 (2003) [6]. J Neugebauer and C G Van de Walle, Appl Phys Lett 69, 503 (1996) [7]. J Oila, et al, Appl Phys Lett 82, 3433 (2002) [8]. O Gelhausen, et al, Phys Rev B 69, 125210 (2004)

4:45 PM E5.11
Photoluminescence study of plastically deformed GaN.
Ichiro Yonenaga[1], Michio Makino[1], Shun Itoh[1], Takenari Goto[2] and Takao Yao[2]; [1]Institute for Materials research, Tohoku University, Sendai, Japan; [2]CIR, Tohoku University, Sendai, Japan.

Dislocations affect to the electronic and optical properties of III-V nitrides and are key topics for developing the relevant devices. However, even now, several theoretical works on the topics are in controversy since experimental attempts to clarify the intrinsic properties of III-nitrides are limited. We report the photoluminescence studies on the fresh dislocations induced by the plastic deformation in GaN crystals. GaN crystals prepared from free standing wafers grown by the HVPE technique were compressed plastically at 900 to 1000C. In the deformed crystals (a/6)<11-20> type edge dislocations on the {1-100} slip plane were dominantly observed in TEM observations. Such dislocations just correspond to so-called threading dislocations in as-grown GaN films on substrates. In the PL studies at 11K and at room temperature the band-edge emission intensity decreased drastically in the deformed specimens by about 1/100 than that of as-grown GaN, which seems to imply the introduction of a high density of non-radiative recombination centers into GaN during the plastic deformation. By the plastic deformation YB were observed to decrease strongly while RB developed relatively, which seems to imply that RB is originating in a dislocation in GaN.

SESSION E6: Transistors
Chairs: David Cassagne and Michael Manfra
Wednesday Morning, December 1, 2004
Back Bay C (Sheraton)

8:30 AM *E6.1
Deep-Submicron Gate-Recessed and Field-Plated Algan/Gan Hfets for mmwave Applications. Jeong Moon[1], Shihchang Wu[2], D. Wong[1], I. Milosavljevic[1], P. Hashimoto[1], M. Hu[1], M. Antcliffe[1] and M. Micovic[1]; [1]HRL Laboratories, Malibu, California; [2]Boeing Satellite Systems, El Segundo, California.

Recently, AlGaN/GaN-based HEMTs demonstrated RF power performance as high as 30 W/mm at 8 GHz with field-plating (FP) or overlapping gates.[1] A proper optimization of field-plates is necessary to operate FP GaN HFETs at higher frequencies well beyond X-band. For real system insertion, along with device reliability and reproducibility, PAE is a very important figure of merit. At high frequency bands such as K, Ka-, Q-, and V-band, there has been very limited data on device performance with both high power density and high PAE, simultaneously. The output power, for instance at Vds = 28 V, is limited to well below theoretical maximum, thus limiting PAE. The poor power scaling might be attributed to high field induced trapping under high Vds and high RF power operation. Thus, by separating the gate plane from surface states, the recessed-gate AlGaN/GaN devices expect to improve the power scaling and PAE, along with an improved device transconductance. The deep_submicron gate-recessed and FP AlGaN/GaN HFETs were fabricated using SiNx masking and Cl2 plasma etching, similar to the process reported in 2002 [2], on the materials grown on semi-insulating (0001) 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 -2 V. The measured extrinsic transconductance was as high as 600 mS/mm, comparable to that of GaAs PHEMTs. Small signal RF measurements showed a unity-gain cut-off frequency (fT) of 60 GHz, and maximum oscillation frequency (fmax) of 100 GHz, respectively, with Lg = 0.2 um. In addition, excellent maximum-stable-gain (MSG) scaling up to 1mm 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 measured DE and PAE at P1dB was as high as 58 % and 45 % at a power density of 5.7 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 Dietrich.

9:00 AM E6.2
GaN Devices for High-Efficiency High Power X-band Radar Performance Enhancement Grown on High Thermal Conductivity AlN Substrates. W. Stacey[1], P. Lamarre[1], J. Murguia[3], Vladimir Tassev[3], C. Thomidis[2], W. Li[2], Theodore D. Moustakas[2], J. Lorenzo[4], D. Bliss[4] and Q. Sun-Paduano[4]; [1]Photronix Inc., Waltham, Massachusetts; [2]Boston University, Boston, Massachusetts; [3]Solid State Scientific Corporation, Hollis, New Hampshire; [4]Air Force Research Laboratory, Bedford, Massachusetts.

A novel GaN device for advanced T/R Modules for X-band radar consisting of n-type and p-type GaN epitaxial layers grown on AlN substrates is described. This work will present performance data for GaN based diodes on AlN substrates and GaN n-p-n transistors on SiC substrates. Most of the waste heat in a transceiver (Transmit/Receive) module is from the power output stage. With the introduction of power output stages fabricated from GaN with other wide bandgap semiconductor materials, notably AlN, there is the possibility of increasing power and efficiency. It is a goal of this work to decrease the amount of hardware and logistics required to support large cooling systems currently needed for inefficient transceiver modules, reduce costs for implementing these large cooling systems and additionally provide more compact, reliable, efficient, powerful, low cost x-band radars for military and commercial power semiconductor applications. The front-illuminated GaN n-p-n mesa transistors are fabricated from multilayer GaN films grown by MBE onto 1 cm by 1 cm AlN templates. Mesas are etched by the Inductively Coupled Plasma (ICP) process to assure minimal damage at the mesa surface. MBE growth conditions have been optimized for GaN films grown on AlN substrates to achieve diode structures that show good diode response from 15C to 456C, reverse saturation current Io = 0.87 uA, ideality n = 1.4, and reasonable activation energy on our first n-p-n transistor: Activation energy = 0.72 eV Novel wafer processing has been developed for these devices, with excellent uniformity and control of ICP dry etch depth. The structures were grown at the MBE Laboratory at Boston University. The parts were processed jointly by Photronix and BU. The AlN substrates were supplied by Solid State Scientific Corporation. The SiC substrates were supplied by Cree Inc.

9:15 AM E6.3
AlGaN/GaN Field Effect Schottky Barrier Diode for a Low Loss Switching Device. Seikoh Yoshida, Nariaki Ikeda, Jiang Li and Kohji Hataya; Yokohama R&D Laboratories, The Furukawa Electric Co., Ltd., Yokohama, Kanagawa, Japan.

GaN based field effect transistors (FETs) have a very lower on-state resistance and a higher switching speed, and a high breakdown voltage. Therefore, a high efficiency inverter can be realized using GaN based FETs. However, for realizing a high efficiency inverter, not only FETs with a low on-state resistance, but also, a freewheel diode with a very low on-voltage is required to immediately cut off the freewheeling current. The GaN is also effective for a fast recovery or freewheeling diode, since it has a very higher switching speed, and a very low recovery charge. Recently, using SiC, a 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

with a low on-voltage. We have recently proposed a novel field effect Schottky barrier diode (FESBD) with a dual Schottky structure combined with an AlGaN/GaN heterostructure. The feature of this diode is as follows. That is, this diode has a dual Schottky structure is to use a very lower Schottky barrier metal and a higher Schottky barrier metal for obtaining a low on-voltage and a high reverse breakdown voltage, respectively. The on-voltage of diode can be reduced by a low Schottky barrier metal. The leakage current at a reverse bias was suppressed by the pinch-off based on field effect of a higher Schottky barrier metal, resulting in increasing the reverse breakdown voltage. We have already tried a vertical FESBD (VFESBD). It was confirmed that the on-voltage of VFESBD was lower than 0.1V. In this paper, we carried out a planer-type FESBD for a large current operation. The AlGaN/GaN heterostructure was grown by MOCVD. Dual Schottky metals were also the same as a vertical structure. The on-voltage with a dual structure of Ti and Pt was below 0.1 V, although that of only Pt Schottky diode was higher. The reverse breakdown voltage was also over 400 V by pinch-off effect. We thus demonstrated for the first time that the FESBD was operated below a very lower on voltage than 0.1 V and the breakdown voltage was over 400 V. The maximum operation current was over 10 A. The switching time of the diode was shorter than 3 ns. A higher switching speed was confirmed. Furthermore, we fabricated the DC-DC converter using these diodes. The converter property from 12 V to 42 V was successfully obtained using these diodes.

9:30 AM E6.4
AlGaN/GaN HFETs and Insulated Gate HFETs DC and RF Stability. Salih Saygi, Alexei Koudymov, Grigory Simin, Vinod Adivarahan, Shiva Rai, Jinwei 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 is presented. The average time period of the device 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. At the same time, for MISHFETs other factors are limiting the device lifetime. Several test structures such as TLM, gated TLM and MOS-capacitors were tested in order to identify the device degradation mechanism. The device failure was found to be related to the presence of strong electric field near the drain region of the gate of the device. Neither ohmic contact quality, nor the AlGaN/GaN interface 2D electron population density and mobility of the test structures were a subject to degrade during the test. The preliminary stabilization stage of the device parameters was also discovered. This stabilization is usually observed during the first few hours of the device operation and can be attributed to the device training. During the stabilization, the device maximum current drops 10 to 20 %, and the output RF power degrades up to 40 % of the initial value accompanied with the knee voltage run-away process described earlier as one of the important characteristics of so called current collapse. It is shown that the processes responsible for both the stabilization and the time-related failure of the devices are similar to that of the current collapse and lead to the accumulation of the traps in the high field regions of the device buffer.

9:45 AM E6.5
Normally-off operation GaN HFET using a thin AlGaN layer for low loss switching devices. Nariaki Ikeda, Kazuo Kato, Jiang Li, Kohji Hataya and Seikoh Yoshida; Furukawa Electric Co. Ltd, Yokohama, Japan.

The GaN based field effect transistor (FET) can operate under high-power, high-frequency, and high-temperature conditions, since 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 power loss of switching devices such as inverters or converters can be reduced compared with that of using 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 frequency operation, a high-efficiency power supply circuit 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 HFETs. The enhancement mode GaN based HFET using an isolated gate structure was 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. And higher temperature operation was confirmed up to 573K. 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 report, we tried to fabricate 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 a metal organic chemical vapor deposition (MOCVD) method. 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 200mm and the gate length was 2um. The distance of source and drain was over 10um. In this case, the n-type contact layers were not fabricated. When the gate-bias was 0V, Ids was less than 1uA/mm. The breakdown voltage of the HFETs was over 300V. The maximum current was 9A. The Ron was about 30mOHMcm2. Furthermore, by forming a contact layer of source and drain, the operation current of FET is expected to moreover increase. Using these FETs, we successfully demonstrated the DC-DC converter.

10:30 AM *E6.6
Electronic Devices Based on Pyroelectric Nitrides.
Oliver Stefan Ambacher, Center for Micro- and Nanotechnologies, Technical University Ilmenau, Ilmenau, Germany.

High field transport in semiconductors that possess high internal spontaneous and piezoelectric fields opens up a new field of "pyroelectronics". The pyroelectric character of group-III-nitrides with wurtzite crystal structure yields a novel degree of freedom in designing and tayloring devices for modern microelectronic applications. We present both theoretical and experimental studies of III-nitride based sensors, high electron mobility field effects transistors (HEMTs) and resonant tunneling diodes (RTDs) that demonstrate these devices to be optimally suited for high power and high frequency applications. In addition we will demonstrate that the polar surfaces of unpassivated, pyroelectric AlGaN/GaN HEMTs are very suitable for the realization of gas-, polar liquid- and pressure-sensors. Bound sheet charges with high concentrations are induced by gradients of pyro- and piezoelectric polarization at surfaces and interfaces of pseudomorphic AlGaN/GaN hetero- and quantum well structures. These sheet charges can influence the distribution of free carriers and the band edge profiles in GaN based heterostructures significantly and have to be considered for optimum device design and performance of electronic as well as optoelectronic devices. The pyro- as well as the piezoelectric polarization in wurtzite group III nitride alloys are predicted to vary non linear with changing alloy composition, mainly due to different electronegativity of the cations and internal strain effects (varying bond length and angle). To measure polarization gradients in AlxInyGazN/GaN heterostructures we have used the formation of two dimensional carrier gases which tend to compensate positive polarization induced bound sheet charges. We have determined the carrier concentration profiles and electrical transport properties of undoped, silicon and magnesium doped AlGaN/GaN heterostructures by a combination of high resolution X-ray diffraction, atomic force microscopy, Hall effect, C-V profiling and Shubnikov-de Haas measurements. The investigated samples with N- and Ga-face polarity were grown by metalorganic vapor phase deposition (MOCVD) or plasma induced molecular beam epitaxy (PIMBE) covering a broad range of alloy compositions, barrier and quantum well thicknesses. The calculated polarization induced sheet charges based on improved sets of pyroelectric and piezoelectric constants and the sheet carrier concentration for 2DEGs and 2DHGs determined self-consistently from a coupled Schroedinger and Poisson equation will be presented and compared to the experimental values. The influence and relevance of the determined carrier distributions on the performance of AlGaN/GaN based polarization induced HEMTs and resonant tunneling diodes will be discussed. The usefulness of polarization induced interface and surface charges to measure pressure and to design AlGaN/GaN based gas and polar liquid sensors will be presented in addition.

11:00 AM E6.7
High Performance GaN Field-Effect-Transistors Grown by MOVPE with in-situ Si_3N_4 Surface Passivation.
Marianne Germain, Joff Derluyn, Dongping Xiao, Raf Vandersmissen, Johan Das, Wenfei Wang, Steven Boeykens, Maarten Leys, Stefan Degroote, Wouter Ruythooren and Gustaaf Borghs; MCP, IMEC, 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 current degradation, current slump at high drain-source voltage and/or DC to RF dispersion. To minimize the impact of surface states on device operation, passivation of the top AlGaN surface with e.g. SiO_2 or Si_3N_4 (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 piezoelectric nature of III-N devices, the strain state of the overall heterostructure has a direct impact on the channel properties; this includes the strain due to the

Si_3N_4 layer, which changes with growth conditions. On the other hand, reproducibility and homogeneity of the results strongly suffer from a poor control of the AlGaN surface prior 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 Si_3N_4 in the MOVPE reactor, as a last step of heterostructure growth. AlGaN/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 of the two-dimensional electron gas. After growth of the top AlGaN layer, a thin Si_3N_4 layer is grown in-situ at high temperature, using SiH_4 and NH_3 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 Si_3N_4 layer. Transmission Line measurements show a reduction of the ohmic contact resistance and a large improvement of the I-V characteristic uniformity, with sheet resistivity in fair agreement with Hall measurements. Spectacular improvement of the dc characteristics is observed: for a positively biased gate (2 V), the drain-source current density more than doubles from 0.5 A/mm in the reference sample to 1.2 A/mm with in-situ passivation, for a device width of 100 μm and a gate length of 0.2 μm. RF measurements show a f_t of 36 GHz and f_{max} of 80 GHz, for the same device geometry. This improvement in device performance thanks to in-situ Si_3N_4 deposition will be compared to results obtained with ex-situ Si_3N_4 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 E6.8
High Quality AlGaN/GaN/AlN Based HEMT Structures on Bulk AlN Single Crystal Substrates for RF Applications.
Qhalid Fareed[1], Xuhong Hu[1], Jianyu Deng[1], Remis Gaska[1], Michael Shur[2], Edmundas Koukstis[3] and M. Asif Khan[3]; [1]Sensor Electronic Technology Inc., Columbia, South Carolina; [2]Dept of ECE and CIE,, Rensselaer Polytechnic Institute, Troy, New York; [3]Dept. 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 HEMT devices 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 AlN single crystal are promising and viable substrate for high power, and high temperature electronic devices. The use of a bulk AlN substrate should allows us to reduce the dislocation density in the epitaxial layers by more than four orders of magnitude down to 10^4-10^5 /cm^2. At the same time bulk AlN substrates have superior thermal conductivity (3 W/cm-K or higher) comparable to that of semiinsulating 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 AlN single crystal substrate. The homoepitaxial AlN 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 layer compared to MOCVD layer with 2-3 orders of magnitude reduction in deep level peak. Atomic force microscopy(AFM) studies on AlGaN/GaN heterostructure show a root mean square roughness less than 8Å. The ω-2Θ rocking curve measurement shows full width half maxima of less than 50 arc sec for homoepitaxial AlN 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 epilayers. 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 AlN substrate will be building blocks for a new generation of ultra-high microwave power amplifiers.

11:30 AM E6.9
Location of Deep Defects in AlGaN/GaN High Electron Mobility Transistors on Si Substrates and their Impact on Device Performance. Hartmut Witte[1], K.-M. Guenther[1], A. Krtschil[1], A. Dadgar[1], A. Krost[1], J. Christen[1], A.T. Winzer[2] and R. Goldhahn[2]; [1]Institute of Experimental Physics, Otto-von-Guericke-University Magdeburg, Magdeburg, Germany; [2]Institute of Physics, Technical University Ilmenau, Ilmenau, Germany.

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 alloy fluctuations in the AlGaN layers. A crucial and still unsolved 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 one the 2 DEG electron mobility is larger than 800 cm2/Vs, whereas for the second group the 2 DEG is disturbed 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 the latter the rise and decay time constants yield information about the trap densities. 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 theses traps are in the range between 100 meV and 600 meV.

11:45 AM E6.10
Thermal Mapping of Defects in AlGaN/GaN HFETs.
M. Kuball[1], J.W. Pomeroy[1], M.J. Uren[2], T. Martin[2], R.S. Balmer[2], D.J. Wallis[2], K.P. Hilton[2], Grigory Simin[3] and M. Asif Khan[3]; [1]H.H. Wills Physics Laboratory, University of Bristol, Bristol, United Kingdom; [2]QinetiQ Ltd, Malvern, United Kingdom; [3]Department of Electrical Engineering, University of South Carolina, Columbia, South Carolina.

Self-heating in AlGaN/GaN HFETs is an important factor that influences device reliability and performance. A micron/sub-micron spatial resolution thermal mapping technique such as micro-Raman spectroscopy is needed to study the temperature variation across the small source-drain opening in these devices, or to study local effects of defects on device temperature. The required spatial resolution goes beyond that typically achievable with IR imaging techniques. The effect of defects on AlGaN/GaN HFET device temperature grown on SiC substrates was studied. Mapping of device temperature was performed on devices situated in the vicinity of micro-pipes in the underlying SiC substrate. These devices showed significant local temperature variations. For example, for a device operated at about 1.8W, device temperature reached about 130°C in the vicinity of a micro-pipe, although the average device temperature was only about 100°C. The experimental results were in good agreement with thermal finite difference simulations when considering zero thermal conductivity in the vicinity of the defect. This suggests that a reduced thermal conductivity of the SiC and the GaN near the defect is likely to be responsible. Also temperature variations in ensembles of AlGaN/GaN HFETs grown on SiC wafers were studied to investigate how homogeneous the device temperature is over a full wafer, considering that defect density can vary throughout the SiC substrate. For one of the wafers we found a temperature distribution FWHM as large as 30°C for an average device temperature of about 100°C for devices operated at 1.8W. Defects and surface passivation effects will be discussed as the origin for these temperature variations.

SESSION E7: Photonic Applications
Chairs: Axel Hoffmann and Yoichi Kawakami
Wednesday Afternoon, December 1, 2004
Back Bay C (Sheraton)

1:30 PM *E7.1
Enhancement of Second Harmonic Generation in One-Dimensional and Two-Dimensional GaN-based Photonic Crystals. Jeremi Torres, Dominique Coquillat, Rene Legros, Jean Lascaray, Marine Le Vassor D'Yerville, Emmanuel Centeno, David Cassagne and Jean-Paul Albert; Groupe d Etude des

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 damage thresholds. However, the use of III-nitrides 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. Periodic lattices of stripes or holes 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 planar 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 beam at the fundamental frequency ω excites a resonant Bloch mode and the second-harmonic field generated is coupled into a resonant Bloch mode at 2ω. A smaller, but still substantially enhanced, second-harmonic generation level was also observed when the fundamental field was coupled into a resonant 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 transparency window of III-nitride wide-bandgap semiconductors, 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 diameter/periodicity as small as 100/180 were patterned to realize PCs 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 LEDs at 299 nm. It was observed that the optical enhancement factor depends strongly on the photonic crystal lattice constant and hole size. In comparison to the blue PC-LEDs with the optical enhancement factor of about 1.63, PCs extract light more effectively from III-nitride UV/deep UV LEDs yielding higher enhancement in optical power. As most of the light generated on the III-nitride deep UV LEDs (with high Al content) emits in-plane and is trapped as guided mode by the layers of semiconductor, PCs is more effective to extract the light from deep UV LEDs. The angular distribution of light emission from LEDs with PCs shows slight narrowing in far-field pattern. Time-resolved electroluminescence (EL) spectroscopy was employed to study the effect of photonic crystal formation on the transient responses of LEDs. With the incorporation of PCs on LEDs, the EL decay time constant τ decreases systematically with the increase of the etched sidewall area indicating the strong effect of the surface recombination. The surface recombination velocities on the p-type GaN epitaxial surface and on the sidewall of etched holes on LEDs were determined to be 1.73 x 10^4 cm/sec and 1.48 x 10^5 cm/sec respectively. Because of the faster transient response along with enhanced light extraction, the incorporation of PCs in UV LEDs provide an effective method to control the modulation speed of UV LEDs, which could be very useful for many applications. The PCs fabricated on MOCVD grown AlN epilayers, which can be used to manipulate light with wavelength as small as 200 nm, will also be discussed.

2:15 PM E7.3
All-Optical Switches Based on Intersubband Transitions in GaN/AlGaN/AlN Multiple Quantum Wells for Tbit/Sec Operation. Jahan M. Dawlaty, 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/AlGaN/AlN multiple quantum well structures. Devices that are currently used for all-optical signal processing are not suitable for operation at data rates beyond 80 Gb/s. Optical fiber based devices, although fast, require pulse energies of several tens of pJs for switching as a result of the small fiber nonlinearities [1]. Devices based on interband transitions in semiconductor optical amplifiers (SOAs) [2] 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] which allow for the realization of ultrafast optical devices. We have realized intersubband optical devices close to telecommunication wavelengths (1.55 μm) in GaN/AlGaN/AlN quantum wells grown on AlN and AlGaN buffer layers on sapphire substrates. As a result of the fast electron intersubband relaxation rates and large intersubband optical oscillator strengths, these devices are capable of switching speeds close to 1 Tb/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-loss modulation and cross-phase modulation in integrated GaN/AlGaN optical waveguides. We will show extinctions ratios (between logical 1 and 0) better than 15 dB at data rates as high as 1 Tb/s. The growth of GaN/AlGaN quantum wells on AlN and AlGaN buffer layers allows minimization of material strain and optimization of the polarization-induced electric fields in the quantum wells resulting in improved optical dipole matrix elements between the upper and lower subbands. We also show optimized designs for a variety of ultrafast all-optical devices such as electro-absorption modulators, wavelength converters, and devices for all-optical pulse retiming, reshaping, and reamplification (3R generation), based on the above mentioned material. 1.J. P. Skoloff, P. R. Prucnal, I. Glesk, M. Kane, "A terahertz optical asymmetric demultiplexer (TOAD)," IEEE Photonics Technol. Lett., vol. 5, 787-790(1993). 2.R. J. Runser, D. Zhou, C. Coldwell, B. C. Wang, P. Toliver, K. Deng, I. Glesk, P. R. Prucnal, "Interferometric ultrafast SOA based optical switches - From devices to applications," Optical and Quantum Electronics, vol. 33, 841-874(2001). 3.K. Tajima, S. Nakamura, Y. Ueno, "Ultrafast all-optical signal processing with symmetric Mach-Zehnder type all-optical switches," Optical and Quantum Electronics, vol. 33, 875-897(2001). 4.J. Faist, F. Capasso, C. Sirtori, D. L. Sivco, A. L. Hutchinson, A. Y. Cho, "Vertical transition quantum cascade laser with Bragg confined excited state," Appl. Phys. Lett., vol. 66, 538-540(1995).

2:30 PM E7.4
The Ga-Nitride/air Two-Dimensional Photonic Quasicrystals Fabricated on GaN-based Light Emitters. Bei Zhang, ZhenSheng Zhang, Jun Xu, Qi Wang, ZhiJian Yang, WeiHua Chen, XiaoDong Hu, ZhiXin Qin, GuoYi Zhang and DaPeng Yu; Physics, Peking University, Beijing, China.

Currently, the photonic crystal composed by quasicrystal structure attracts much interest. The photonic quasicrystal (PQC) has high-order rotational and line 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 lower air rod fill factor and/or lower refractive index contrast It makes photonic quasicrystals promising for application in a variety of optical devices. However, few reports on the GaN-based 2D PQC can be found due to the big technical challenge in fabricating at 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 PQCs made on the GaN-based multiple quantum-well light emitters were investigated. Focused Ga ion beam (FIB) milling is a useful 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 patterning was found to be dependent on the ion dosage and the air hole fill factor. A careful balancing of milling hole radius and electron dosage was taken to realize the required patterns. The 8-fold and 12-fold air/GaN photonic quasicrystals were successfully fabricated. Depending on a variety of etching depths from 90nm-370nm, the 8-fold and 12-fold PQC structures had hole radii from 50nm up to 570nm with the air hole fill factor about 10 to 40%. The area of the PQC squares varied from $(6um)^2$ to $(30um)^2$. Among these, the nearest center-to-center distance of the holes and/or the lattice constant was 170nm. As a result, FIB milling provides a promising technique for preparing GaN based 2D- phononic quasicrystals with a variety of symmetrical structures. To investigate the light behaviors of these PQCs, several PQCs with different lattice constants and hole diameters were fabricated on the top of edge emitting GaN-based

light emitters. The microscopic fluorescence under UV light excitation and the electrical luminescence under current injection were measured from the edge and top of the devices. The effects of the PQCs on blocking the guided modes and enhancing the surface escaped modes were observed. Three-fold enhancement of surface emission was demonstrated in the PQC patterned GaN-based light emitters. The detail comparison of the results was given and discussed.

2:45 PM E7.5
Photoelectrochemical etching of GaN as a tool for smooth etching and formation of pores and wires. Ion Tiginyanu[1,2], Veaceslav Popa[1], Olesea Volciuc[1], Oleg Cojocari[3], Veaceslav Ursaki[2], Dimitris Pavlidis[3] and Hans Hartnagel[3]; [1]Laboratory of Low Dimensional Semiconductor Structures, Technical University of Moldova, Chisinau, Moldova; [2]Institute of Applied Physics, Academy of Sciences of Moldova, Chisinau, Moldova; [3]Technical University Darmstadt, Darmstadt, Germany.

GaN and related nitrides are considered promising for numerous applications such as the creation of full-color display systems, data storage devices, solar-blind ultraviolet detectors, new sensor technologies, wireless communications, solid-state lighting and high-power microwave generation for radar, etc. Note that nitride-based light-emitting diodes and lasers have been successfully commercialized. Further elaboration of novel device structures on GaN depends primarily upon the progress in growth technologies and material nanostructuring. In this work, we show that photoelectrochemical (PEC) etching is an efficient and cost-effective tool for GaN smooth etching and nanostructuring. We performed a comparative study of GaN PEC etching in different solutions based on KOH, HF, oxalic acid, etc. Doped and undoped epilayers grown by metalorganic chemical vapor deposition on sapphire or SiC substrates were used. The morphology of PEC etched samples was studied as a function of the wavelength and intensity of in-situ UV illumination as well as a function of composition, temperature and stirring of the electrolyte. Depending upon etching conditions, honeycomb-like porous layers or GaN columnar structures were fabricated and explored using scanning electron and atomic force microscopes. Under proper additional etching the GaN columnar structures prove to be transformed into GaN wool consisting of GaN nanowires with the length of up to several micrometers. Conditions for smooth etching of GaN were evidenced and different types of GaN mesostructures for concrete applications were fabricated. In particular, Pt/GaN Schottky diodes for high frequency applications are demonstrated. Uniformly distributed nanopores stretching perpendicular to the initial surface were introduced in GaN epilayers, thus openning the possibility to use the samples as nanotemplates for nanofabrication. Data concernig chemical composition and crystalline quality of GaN porous structures and nanowires are presented. New results related to the possibilities for nanostructuring-induced optical phonon engineering and modification of GaN luminescence characteristics [1,2] are discussed. This work was supported by the U.S. Civilian Research and Development Foundation under Grant # MR2-995 and by BMBF, Germany. [1] I.M. Tiginyanu et al, Phys. Rev. B 64, 233317 (2001); Appl. Phys. Lett. 83, 1551 (2003).

3:30 PM *E7.6
Strong Rabi Splitting and Polariton Lasers in Nitride-Based Microcavities. Alexey Kavokin and Guillaume Malpuech; LASMEA, Blaise-Pascal University, Aubiere, France.

The exciton oscillator strength in GaN exceeds by an order of magnitude the oscillator strength in GaAs. That is why the light-exciton coupling strength in nitride based structures is expected to be extremely large. With excitons stable at room temperature, GaN-based microcavities are the most promising candidates for realization of polariton lasers: light emitters of a new generation, able to produce the coherent and monochromatic light by spontaneous emission from the exciton-polariton condensates. In 2003-2004 the first experimental observations of the strong-coupling regime in nitride based microcavities have been reported in literature. I am going to adress the optical properties of future polariton lasers based on GaN, namely the second order coherence and polarization of emitted light. I will show theoretically that Bose-condensation of exciton-polaritons may lead to the spontaneous coherence build-up and spontaneous appearance of a strong liner polarisation in emission of the microcavities. Polariton effect on the conductivity in the electron-hole plasma will be discussed as well.

4:00 PM E7.7
Crack-Free Monolithic Nitride Microcavity using Highly Reflective AlInN/GaN Bragg Mirrors. J.-F. Carlin, Eric Feltin, J. Dorsaz, R. Butte, N. Grandjean and M. Ilegems; Institute for Quantum Electronics and Photonics, Swiss Federal Institute of Technology, Lausanne, Vaud, 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 a first step towards the demonstration of strong 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 $3\lambda/2$ GaN cavity with two sets of 3 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 as the low index layer of a lattice-matched $Al_{0.82}In_{0.18}N$ alloy instead of $Al_xGa_{1-x}N$ layers prevents 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 $Al_xGa_{1-x}N$ 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) pairs 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 optimal properties (linewidth and oscillator strength) of the InGaN/GaN QWs required to achieve strong light-matter coupling in such a structure will be investigated.

4:15 PM E7.8
Crack-free Nitride-based Distributed Bragg Reflectors Grown on Patterned Substrates. Carsten Kruse, Stephan Figge, Sven Einfeldt, Claudia Roder, Jens Dennemarck and Detlef Hommel; Institute of Solid State Physics, University of Bremen, Bremen, Germany.

High-reflectivity distributed Bragg reflectors (DBRs) are of particular interest concerning the realization of 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 by plasma assisted molecular beam epitaxy (PAMBE) on GaN/sapphire template layers previously fabricated by metal-organic vapour-phase epitaxy (MOVPE). The DBRs consist of 42.5 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 quasi-ternary alloy with a dispersion of Al(0.60)Ga(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 AlGaN 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 stopband 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, mesas of 25 μm x 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. For a direct comparison, a part of the substrate has been left unstructured. DBR structures as described above were successfully deposited on these mesas without the formation of cracks and showed a sufficiently smooth surface according to RHEED. In contrast, the unpatterned 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 In 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 1μm. Tetsuo Fujii[1], Aurelien David[2], P. Morgan Pattison[2], Steven P. DenBaars[1,2], Claude Weisbuch[2] and Shuji Nakamura[1,2]; [1]NICP/ERATO JST, UCSB Group, University of California Santa

Barbara, Santa Barbara, California; [2]Materials Department, University of California Santa Barbara, Santa Barbara, California.

The use of micro cavities in light-emitting diodes brings us the possibility of controlling the spontaneous emission characteristics in spectral intensity, purity, directivity and so on. In particular, we are focusing on increasing the light extracty

4:45 PM E7.10
Nanoscale Imaging of $In_xGa_{1-x}N$ Thickness Fluctuations and In Clustering in $In_xGa_{1-x}N$/GaN Quantum-well Structures Using SCM. Xiaotian Zhou[1], E. T. Yu[1], D. I. Florescu[2], J. C. Ramer[2], D. S. Lee[2] and E. A. Armour[2]; [1]Electrical and computer engineering, University of California, San Diego, La Jolla, California; [2]Veeco TurboDisc Operations, Somerset, New Jersey.

$In_xGa_{1-x}N$/GaN quantum-well structures are of outstanding current interest for nitride semiconductor-based visible light emitters. Because of the high densities of point and extended defects in epitaxially grown nitride semiconductor material, characterization and understanding of local, nanoscale structure and electronic properties in such devices is essential to achieve effective control over and optimization of device characteristics and performance. We have used scanning capacitance microscopy (SCM) and atomic force microscopy (AFM) to characterize structural and electronic properties of $In_xGa_{1-x}N$/GaN quantum-well structures at the nanoscale. Samples consisting of a 2-3mm n-GaN buffer layer followed by a 30Á-35Á $In_xGa_{1-x}N$ quantum-well layer capped with 20Á GaN were grown by MOCVD on sapphire substrates. InxGa1-xN quantum wells with x=0.30 and x=0.15 were studied. The proximity of the quantum-well layer to the sample surface allows very high spatial resolution to be attained. Macroscopic capacitance-voltage measurements combined with numerical simulations indicate that while the quantum-well layer is depleted at zero bias, either electron or hole accumulation in the quantum-well layer can be induced by application of forward or reverse bias, respectively. SCM and AFM imaging on the MOCVD reveal localized depletion of electrons in the vicinity of threading dislocations, indicating that dislocations in these samples contain negative charge in their core. In addition, variations in local carrier density within the InxGa1-xN quantum-well layer are observed that appear to reflect the atomic step structure visible on the GaN surface. A detailed analysis of SCM and AFM image data as well as spatially resolved scanning capacitance spectra suggests that these variations arise from monolayer fluctuations in $In_xGa_{1-x}N$ quantum-well thickness. Thus, we are able to image subsurface layer thickness variations at the monolayer level via their influence on local carrier distributions. SCM images under forward bias of an $In_{0.15}Ga_{0.85}N$/GaN quantum well structure revealed the presence of randomly distributed round features with a density of approximately $10^9 cm^{-2}$. Comparison of bias dependent SCM images with results of numerical simulation indicates that these features correspond to localized In rich clusters in the InGaN quantum well, within which increased electron accumulation occurs.

SESSION E8: Poster Session
Wednesday Evening, December 1, 2004
8:00 PM
Exhibition Hall D (Hynes)

E8.1
Ultraviolet Raman Scattering of GaN Nanocrystallites: Intrinsic versus Collective Phenomena. Xiang-Bai Chen[1], John L. Morrison[1], Jonathan G. Metzger[1], Jarvis Weaskus[1], Leah Bergman[1] and Andrew P. Purdy[2]; [1]Physics Department, University of Idaho, Moscow, Idaho; [2]Chemistry Division, US Naval Research Laboratory, Washington DC, District of Columbia.

Resonant Raman scattering in GaN nanocrystallites of various morphologies was studied. The A1(LO) polar mode exhibited Frohlich-type resonant Raman scattering and its characteristics were found to depend weakly on the morphology of the crystallites. UV-laser heating and heat retention in the porous media of the crystallites were found to drastically modify the Raman properties; redshifts in the Raman spectra of up to 8 wavenumbers were observed and attributed to this thermal effect. Photoluminescence studies concurred with these findings. Ensemble temperatures of the order of 550 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 free carrier concentration of the nanocrystallites that was inferred from the phonon-plasmon interaction was found to be significantly lower than in GaN films.

E8.2
High-Quality, Low-Cost Continuous Poly-GaN Film on Si an Glass Substrate Produced by Spin Coating. Huaqiang Wu[1], Athanasios Bourlinos[2], Emmanuel P. Giannelis[2] and Michael G. Spencer[1]; [1]Electrical and Computer Engineering, Cornell University, Ithaca, New York; [2]Materials Science and Engineering, Cornell University, Ithaca, New York.

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. This GaN powder has a unique platy morphology. The aspect ratio, plate dimension (a direction) to plate thickness (c 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 cellulosic dispersant, 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 orientated. 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 surface 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.

E8.3
Role of Band-Tails in Photoluminescence of AlGaN Epilayers in a Wide Range of Alloy Composition, Temperatures and Excitations. Edmundas Kuokstis, Wenhong Sun, Maxim Shatalov, Jiawei Li, Jinwei Yang and M. Asif Khan; Electrical Engineering, University of South Carolina, Columbia, South Carolina.

Ternary AlGaN alloys have captured much attention due to their potential application in optoelectronic devices in ultraviolet region. However two major problems limit their usage. First, growing of high quality of nitride alloys (crack-free, low defect and alloy disorder level) is still challenging and needs new approaches. Second, the light emitting mechanisms are not completely understood in AlGaN compounds. In this work, we analyze AlGaN samples prepared using different approaches in metalorganic chemical vapor deposition (MOCVD). Insertion of strain-relief interlayer of superlattice (SL) in a buffer layer over *c*-plain sapphire enabled us to fabricate high quality alloys with any Al fraction. These layers exhibited sharper lines in XRD picture, as well as sufficiently stronger photoluminescence (PL) intensity in comparison with layers prepared by conventional MOCVD approach without introduction of SL. These AlGaN epilayers featured lower density-of-states tails along with lower rate of nonradiative recombination. We have analyzed in detail the PL of these AlGaN alloys in a wide temperature range (7-300K) and excitation power densities (from 20 W/cm^2 to 2 MW/ cm^2) using excimer laser (λ = 193 nm, τ = 8 ns). The observed typical band-tail related *s*-shape temperature dependences, spectra evolution with excitation intensity, PL polarization analysis along with theoretical model calculations enabled us to evaluate specific band-tail parameters in different samples with various composition. In particular, we calculated total amount of band-tail states, as well as deviation of the potential fluctuations and compared them in different sets of samples. Our results confirm high potential of ternary AlGaN compounds for application in deep UV optical devices.

E8.4
AlN Bulk Crystal Growth on SiC Seeds. Rafael Dalmau, Raoul Schlesser and Zlatko Sitar; 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 epilayer that was intended to suppress premature decomposition of SiC seeds exposed to Al vapor and 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 1850-2000°C and at a constant reactor pressure of 600 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. Crack-free crystals were obtained from thick (> 2 mm) layers grown 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 nm RMS roughness as determined by AFM. Bulk AlN layers were analyzed by glow discharge mass spectrometry to determine contaminant levels, such as oxygen (500-1200 ppm wt), carbon (160-300 ppm wt), and silicon (130-200 ppm wt). The influence of substrate orientation on AlN growth was also evaluated. Experiments 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 μm-wide terraces characteristic of step-flow growth, and rough regions containing large, millimeter-wide hexagonal hillocks. Wet chemical etching was used to reveal the polarity of different regions. AlN grown on Si-face SiC was primarily Al-polar (c+) but contained N-polar (c−) inversion domains, as revealed by wet etching in hot, aqueous phosphoric acid or potassium hydroxide solutions. Inversion domains were 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. Francesca Carosella[1], Marianne Germain[2] and Jean-Louis Farvacque[1]; [1]Universite' des Sciences et Technologies de Lille, CNRS UMR 8008, Villeneuve d' Ascq, France; [2]IMEC, 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 remain 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 plasmons which, when damped, constitute now a real relaxation mechanism. Following the Kim et al. 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 mechanisms associated with hybrid phonon/plasmon particles. Using simple arguments, we, first, generalize the 3D Kim' s approach to the case of 2-dimensional multi subbands systems. Then, our calculation is based i) on the knowledge of the wave functions 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, plasmons 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 μ 2500 cm^2/Vs for an areal carrier density $n_s = 4{\cdot}10^{12}$ cm^{-2} and around 3000 cm^2/Vs for $n_s = 2{\cdot}10^{13}$ 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 best experimental results will be shown and discussed. [1] M.E. Kim, A. Das and S.D. Senturia, Phys. Rev. B 18, 6890, 1978

E8.7

Strain and Bow Management of GaN Optoelectronic Devices Grown on 4 inch Sapphire. C. Sommerhalter[2], H. Protzmann[1], M. Luenenbuerger[1], J. Kaeppeler[1], B. Schineller[1] and Michael Heuken[1]; [1]AIXTRON AG, Aachen, Germany; [2]AIXTRON Inc., Buffalo Grove, Illinois.

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 eight 4 inch wafers, effectively increasing the usable wafer area from 300 in^2 to 400 in^2 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 2 inch wafers, it tends to become more severe as the wafer size is increased causing the wafer to loose contact to the MOCVD tool's heated graphite susceptor when the device layers become thicker. This, in turn, can lead to temperature deviations across the wafer, which are especially undesirable in the growth of InGaN structures. To remedy these effects, careful engineering of the MOCVD tool along with intensive investigations on the properties of the wafer, its surface and miscut angles were conducted. The influence of the sapphire wafer thickness (investigated thicknesses were 500 μm, 640 μm and 850 μm) was found to be a dominant factor for the uniformity of the photoluminescence wavelength, with thicker wafers showing less influence of layer induced bow during the growth run. To assess the influence of the intentional miscut of the sapphire surface on the process window, wafers with miscuts of 0°, 0.2°, 0.3° and 0.4° towards m- and a-plane were investigated. Growth temperatures of the GaN were varied between 1100°C to 1160°C. Contactless sheet resistance mappings using a Lehighton Model 1510, Hall-effect measurements and optical microscopy of the surface morphology of GaN single layers were used for assessment. It was found that wafers with miscuts of 0.3 to 0.4° towards the m-plane exhibited the best surface morphology and best electrical quality and were most stable for the growth temperatures investigated. Finally, to demonstrate the performance of the system under optimised hardware, wafer and process conditions, 5 period InGaN/GaN multi-quantum well structures were grown and characterized. At an average photoluminescence wavelength of 498 nm a standard deviation of the peak position of 2.9 nm was achieved on a 4 inch wafer with 3 mm edge exclusion for a 5 μm thick structure. We will report in detail on the performance of the 8x4 inch configuration of the AIX 2600G3 HT covering the above mentioned issues of wafer strain and surface properties.

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 silane 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 reduction mechanisms of TDs in GaN have been 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 enhances the lateral growth, and islands 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 $8{\times}10^7$ cm^{-2}, as 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.

E8.9

Effect of Edge Dislocations on Polarization Dependent Loss of MBE-grown GaN Ridge Waveguides at Optical Communication Wavelengths. Norio Iizuka, Kei Kaneko and Nobuo Suzuki; Corporate R & D Center, Toshiba, Kawasaki, Japan.

GaN-based intersubband transition (ISBT) is of great interest for ultrafast optical device applications. The ISBTs at optical communication wavelengths have previously been reported and the carrier relaxation time has been measured at considerably less than 1 ps. Since the ISBT occurs only for TM-polarization, the background propagation 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 ISBTs have been achieved at optical communication wavelengths only with MBE-grown MQWs, 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 the re-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. PDL was evaluated with a CW laser source at a wavelength of 1.55 μm. The insertion losses for TM-polarization were greater than those for TE-polarization, and the PDL strongly depended 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 nitridation at 300 °C. The PDL improved to -11 dB for the sample nitrided at 540 °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 $5x10^{18}$ cm^{-3}. We believe that the edge dislocations were distributed perpendicularly in the epitaxial layer, and gathered 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 gathered more carriers, and intensified the polarizer effect. 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. Thus 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^{9} 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 reduced the PDL. This 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 New Energy and Industrial Technology Development Organization (NEDO).

E8.10

Microstructure of Highly p-Type Doped GaN Sub-Contact Layers for Low-Resistivity Contacts. Roland Kroeger[1], Jens Dennemarck[1], Stephan Figge[1], Tim Boettcher[1], Detlef Hommel[1], Eliana Kaminska[2] and Anna Piotrowska[2]; [1]Institute of Solid State Physics, University of Bremen, Bremen, Germany; [2]Institute of Electron 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. These defects form, as was previously shown [1], if a critical Mg to group III molar flow 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 dependance sub-contact layers were grown with different Mg to group III flow ratios. Using Pd/Au contacts and a molar flow ratio 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 Mg doping 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 showed for the low resistivity contacts a smooth interface and no pyramidal defects in the highly doped area, explaining the efficient p-type conductivity. Moreover, a low contrast region of about 5 nm thickness could be observed at the interface between the GaN and the metal contact, which is assigned to an alloying of the Pd/Au contact with the Mg: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 16 (2002).

E8.11

Dislocation Nucleation and Subsequent Annihilation in MOCVD-Grown GaN Films and AlN Nucleation Layers on 4H-SiC Patterned Mesa Substrates. Nabil D. Bassim[1], Mark E. Twigg[1], Charles R. Eddy[1], Phillip G. Neudeck[2], Michael A. Mastro[1], Richard L. Henry[1], James C. Culbertson[1], Andrew J. Trunek[3], J. A. Powell[4] and Ronald T. Holm[1]; [1]Electronics Science and Technology Division, U.S. Naval Research Laboratory, Washington, SW, District of Columbia; [2]NASA Glenn Research Center, Cleveland, Ohio; [3]OAI, Cleveland, Ohio; [4]Sest, Inc., Cleveland, Ohio.

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 mesas with MOCVD-deposited GaN layers have been fabricated using focused ion beam (FIB) milling. Our XTEM observations indicate that in addition to having an extremely low density of threading dislocations for heteroepitaxial GaN/SiC growth (8 x107/cm2), the nucleation layer and subsequent GaN films grown on the mesas 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<2110> Burgers vector) to annihilate within 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 a 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 rapid kinetics are able to compensate for impeded nucleation. Low coverage growth experiments of AlN on SiC were performed to determine the dislocation core type and subsequent mobility on stepped and unstepped surfaces. High-resolution transmission electron microscopy studies of the dislocation nucleation behavior in the vicinity of 4H-SiC surface steps will be used to elucidate the role of steps in the development of screw and mixed-type dislocations. We have also developed a model for strain relief (due to the presence of free surfaces 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, 5-10 mTorr nitrogen. Metal targets of aluminum and boron with praseodymium and a liquid target of gallium with solid praseodymium are used. The dominant peaks observed in the visible range result from $^{3}P_0 \rightarrow {}^{3}H_4$, $^{3}P_1 \rightarrow {}^{3}H_5$, and $^{3}P_0 \rightarrow {}^{3}F_2$ transitions with peaks at 488 nm, 526 nm and 652 nm in AlN:Pr, $^{3}P_0 \rightarrow {}^{3}H_4$, $^{3}P_0 \rightarrow {}^{3}H_6$, and $^{3}P_0 \rightarrow {}^{3}F_2$ transitions with peaks at 488 nm, 621 nm and 650 nm in GaN:Pr and from $^{3}P_0 \rightarrow {}^{3}H_4$, $^{3}P_1 \rightarrow {}^{3}H_5$, $^{3}P_0 \rightarrow {}^{3}H_6$, and $^{3}P_0 \rightarrow {}^{3}F_2$ transitions with peaks at 492 nm, 544 nm, 628 nm and 651 nm in BN:Pr. Additional peaks are observed from AlN:Pr at 335 nm and 383 nm from $^{1}S_0 \rightarrow {}^{1}D_2$ and $^{1}S_0 \rightarrow {}^{1}I_6$ transitions which are not observed in GaN:Pr and BN:Pr films.

E8.13

Micro-Characterization of GaN and AlGaN on Si(001). Fabian Schulze, Till Riemann, Armin Dadgar, Juergen Blaesing, Juergen Christen and Alois Krost; 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 (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]=0.1) growth, AlN/GaN 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 the variation of the buffer layer design: GaN grows r-plane (10-12) oriented on the Si(001) substrate with four rotational alignments, if a low temperature (630°C) AlN interlayer is used. In contrast, the use of a high temperature AlN (HT-AlN) seed layer results in exclusive c-axis orientation of the hexagonal (Al)GaN. In this case, two rotational in-plane 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 (SEM): For growth on low-temperature buffers, GaN micro-crystals are formed which exhibit rectangular r-plane top facets. In contrast, growth on HT-AlN gives hexagonal top facets. Here, AlGaN forms a fully coalesced layer consisting of 100nm wide nano-crystals, while GaN crystals of 2micron size are still separated from each other. However, merging of the individual AlGaN nano-crystals to a single-crystalline layer is inhibited by their two non-equivalent a-plane orientations, leading to a high density of grain boundaries. 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 (D^oX), GaN grown in the same epitaxial run on Si(001) shows strong lateral fluctuations of the dominant emission process, involving (D^oX) as well as several impurity related emissions. Large GaN micro-crystals on Si(001) are always characterized by intense excitonic CL, proving their high structural and optical quality. For AlGaN on HT-AlN 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.

E8.14

Characterization of P-type Dopants in III-Nitrides by SIMS. Richard S. Hockett[1], Patrick Van Lierde[1], Chunsheng Tian[1], Pablo Cantu Alejandro[2], Stacia Keller[2] and Steven P. DenBaars[2]; [1]Charles Evans & Associates, Sunnyvale, California; [2]Electrical and Computer Engineering and Materials, University of California, Santa Barbara, California.

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 as dopant or impurity, 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 30 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 Mg in a small area, a blue LED was depackaged and prepared for SIMS analysis. III-Nitrides, and AlGaN in particular, suffer from defects due to lattice mismatch with underlying layers or strain introduced during the growth process. The roughness, due to these defects, of the epi surface adversely affects the 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 die was polished on an Allied Tech Products, Inc. MultiPrep 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.

E8.15

Strong Room Temperature 510 nm Emission from Cubic InGaN/GaN Multiple Quantum Wells. Shunfeng Li[1], Donat J. As[1], Klaus Lischka[1], David G. Pacheco-Salazar[2], Jose Roberto Leite[2], Fernando Cerdeira[3] and Eliermes A. Meneses[3]; [1]Department of Physics, University of Paderborn, Paderborn, Germany; [2]Institute of Physics, University of Sao Paulo, Sao Paulo, Brazil; [3]Institute of Physics Gleb Wataghin, University of Campinas, Campinas, Brazil.

Local networks using plastic optical fibres (POF) demand highly efficient light sources which emit at 510 nm (2.43 eV). Nitride based resonant cavity light emitting diodes (RCLED) are promising candidates for this application. To obtain 510nm emission, a relative high In concentration is needed in hexagonal (wurtzite) InGaN. However, III-nitride can also crystallize in cubic (zincblende) configuration. Since the band gap of c-III nitrides is about 0.2 eV lower than that of h-III nitrides, long wavelength emission in c-$In_xGa_{1-x}N$ can be obtained with a lower In content. In this contribution, we report the optical properties of c-$In_xGa_{1-x}N$ double heterostructures (DHs) and quantum wells (QWs). The composition of the $In_xGa_{1-x}N$ layers was measured by high resolution X-ray diffraction (HRXRD). The room temperature photoluminescence (PL) of DHs revealed only a weak shift of the peak energy when the In content was varied between x=0.07 up to 0.18. The minimum full width at half maximum (FWHM) of the PL emission was observed for x=0.13. The PL emission peak energy is well below the alloy band gap measured by photoluminescence excitation spectroscopy (PLE). This suggests that there are In rich structures in the $In_xGa_{1-x}N$ layer which act as highly efficient recombination centres. We find that the PL intensity in our QW structures increases with the well thickness (3 nm -15 nm), a clear evidence for the absence of spontaneous and piezoelectric polarization fields. X-ray diffraction patterns of multiple quantum wells (MQWs) show clearly resolved superlattice peaks. The strong room temperature PL emission of MQWs with x=0.13 had a peak energy of 2.4 eV, demonstrating that these structures can be used as active layers in c-III nitride based RCLEDs.

E8.16

Intense, Long-Lived, Room Temperature Photoluminescence from Localized States in AlGaN Alloys. Charles J. Collins[1], A. V. Sampath[1], G. A. Garrett[1], W. L. Sarney[1], H. Shen[1], M. Wraback[1], A. Y. Nikiforov[2], G. S. Cargill[2] and V. Dierolf[3]; [1]Sensors and Electron Devices Directorate, US Army Research Laboratory, Adelphi, Maryland; [2]Department of Materials Science and Engineering, Lehigh University, Bethlehem, Pennsylvania; [3]Department 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 1μm-thick AlGaN epilayers in the 20-50% Al range 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^{10} 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, as determined by reflectivity measurements. This red-shift is much larger than that typically reported for AlGaN alloys of comparable Al content (10-50meV), often attributed to emission from bandtails associated with alloy fluctuations and structural disorder. While low temperature PL clearly showed both the band edge and red-shifted peak, the peak intensity of the latter only decreased by a factor of 7 from 10K to 300K, while that of the band edge peak decreased by almost 3 orders of magnitude, suggesting 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 In(Al)GaN alloys and attributed to compositional inhomogeneity related to indium incorporation. TRPL data were taken at the red-shifted and band edge peak energies for varying laser pump intensities using subpicosecond luminescence downconversion. The room temperature lifetimes for the 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.

E8.17

High-Quality Thin GaN Layers Directly Grown on Sapphire by HVPE. Denis Martin, Jerome Napierala, Raphael 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 films. Metal-organics vapor phase epitaxy (MOVPE) is currently the growth technique of choice to achieve high-quality GaN material

on sapphire substrate and benefit of a well-established two-step growth procedure. Furthermore the in situ growth monitoring by means of laser reflectivity has been one of the key tools for optimizing the GaN material quality. However the MOVPE growth rate is rather low (typically 2-3 μm/h), 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/h, which is a key advantage over MOVPE for GaN quasi-substrate production. At the present time there is no clear recipe to grow high-quality GaN by HVPE 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 and 271 arcsec for (0002) and (20-24) reflections, respectively. The dislocation density, estimated from cathodoluminescence, is 1x108 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.

E8.18

High Pressure Annealing of HVPE GaN Free-Standing Films: Redistribution of Defects and Strain. Tanya Paskova[1], Tadeusz Suski[2], Michael Bockowski[2], Plamen Paskov[1], Vanya Darakchieva[1], Bo Monemar[1], Filip Tuomisto[3], Kimmo Saarinen[3] and Pierre Gibart[4]; [1]IFM, Linkoping University, Linkoping, Sweden; [2]Unipress, Polish Academy of Sciences, Warsaw, Poland; [3]Helsinki University of Technology, Helsinki, Finland; [4]Lumilog, Vallauris, France.

Free-standing GaN films grown by hydride vapor phase epitaxy (HVPE) are currently the most promising substitution 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 material. The HVPE-GaN films were grown on sapphire using a two-step lateral overgrown metalorganic chemical vapour deposited 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 øC. 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 and 2.2 eV. A study of the distributions of impurity and native Ga-vacancy related defects as well as of the free electron concentrations was performed. The results are critically analysed 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.

E8.19

Spectral Properties of InGaN/GaN-Structures Grown by MOCVD on Non-Planar Si(111) Substrates. Andrea Strittmatter[1], L. Reissmann[1], D. Bimberg[1], T. Riemann[2] and J. Christen[2]; [1]Technical University Berlin, Institute of Solid State Physics, Sekr. PN 5-2, Berlin, Germany; [2]Otto-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 rectangular profile, separated by 4 μm wide ridges, oriented along the Si[1-10] direction. The GaN buffer and finally the InGaN/GaN MQWs are subsequently grown by metal organic chemical vapor deposition. The luminescence spectra emitted from the InGaN/GaN structures are dependant on the spatial position on a μm length scale. Besides local variations of the InGaN luminescence the different local optical matrices surrounding the active layers have to be regarded. Since the bottom interface of the lateral overgrown region is connected to the optically less dense medium air while on the Si ridges the bottom interface is 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 regions 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 absolute peak wavelength which is attributed to slight variations of the air gap inside the grooves leading to varying spectral positions of the cavity modes. Simulations using optical transfer matrices reveal a relatively strong sensitivity of the optical mode distribution to the height of the air gap.

E8.20

Comparison of the Effect of Gate Dielectric Layer on 2DEG Carrier Concentration in Strained AlGaN/GaN Heterostructure. Wenfei Wang[1,2], Marianne Germain[1], Joff Derluyn[1], Ingrid Dewolf[1], Dominique Schreurs[1,2], Wouter Ruythooren[1], Johan Das[1], Raf Vandersmissen[1] and Gustaaf Borghs[1,3]; [1]MCP, IMEC, Leuven, Belgium; [2]E.E., K.U.Leuven, Leuven, Belgium; [3]Physics, 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 Si3N4 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 very strong spontaneous and piezoelectric polarization effect in GaN material system. The surface charge at the top of AlGaN layer has an influence on the 2DEG carrier concentration, and it 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 that 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 Si3N4 layer thickness, varying from 0 to 15 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 Si3N4 on the 2DEG carrier concentration can be explained by the differences between them with respect to charge accumulation at the AlGaN/dielectric interface. Furthermore, Raman spectroscopy shows that no strain is involved in case oxides are used, but high temperature deposited Si3N4-in situ shows strikingly interesting behavior, that it adds more strain to AlGaN/GaN heterostructure, by which increases the piezoelectric polarization in AlGaN top layer and then increases the 2DEG carrier concentration.

E8.21

Partial Dislocations in Wurtzite Structure GaN. Rong Liu[1], Fernando A. Ponce[1], Changqing Chen[2], Jinwei Yang[2] and M. Asif Khan[2]; [1]Dept. of Physics and Astronomy, Arizona State University, Tempe, Arizona; [2]Dept. of Electrical Engineering, University of South Carolina, Columbia, South Carolina.

Epitaxy of GaN along the [11-20] 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 to the standard c-plane growth. In this new geometry, the basal-plane slip system is normal to the growth front, resulting in the generation of high densities of partial dislocations bounding stacking faults. We present a detailed study of the nature of partial dislocations for GaN layers grown by OMVPE on r-plane sapphire using selective area lateral epitaxy. 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 are 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

E8.23
X-ray Characterization of GaN Single Crystal Layers Grown by the Ammonothermal Technique on HVPE GaN Seeds and by the Sublimation Technique on Sapphire Seeds.
Balaji Raghothamachar[1], Michael Dudley[1], Michael Callahan[2], Buguo Wang[2], Phanikumar Konkapaka[3], Huaqiang Wu[3], Michael Spencer[3] and David Bliss[2]; [1]Materials Science & Engineering, Stony Brook University, Stony Brook, New York; [2]Sensors Directorate, Air Force Research Laboratory, Hanscom AFB, Massachusetts; [3]Electrical and Computer Engineering, Cornell University, Ithaca, New York.

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 nitride 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 ammonia atmosphere from a GaN powder source to the sapphire substrate which has a 3-6 micron GaN epilayer deposited on it. Synchrotron 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.

E8.24
Sychrotron White Beam X-ray Topography (SWBXT) and High Resolution Triple Axis Diffraction Studies on AlN Layers Grown on 4H- and 6H-SiC Seeds.
Balaji Raghothamachar[1], Michael Dudley[1], Rafael Dalmau[2], Raoul Schlesser[2] and Zlatko Sitar[2]; [1]Materials Science & Engineering, Stony Brook University, Stony Brook, New York; [2]Materials Science and Engineering, North Carolina State University, Raleigh, North Carolina.

For nitride based devices such as LEDs, high power FETs and laser diodes, single crystal substrates of AlN are highly desirable. While the sublimation technique is suitable for growing bulk AlN 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 AlN 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 resistively heated reactor using on and off-axis 4H- and 6H-SiC substrates as seeds for AlN growth from the vapor phase. Several hundred microns thick AlN layers have been grown under different growth conditions. Synchrotron white beam x-ray topography (SWBXT) has been used to map the defect distribution in the grown layers and high resolution triple axis x-ray diffraction (HRTXD) 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.

E8.25
Atomic and Electronic Structure of Mixed and Partial Dislocations in GaN. Ilke Arslan[1], Andrew L. Bleloch[2], Eric A. Stach[3] and Nigel D. Browning[4,3]; [1]Department of Materials Science and Metallurgy, University of Cambridge, Cambridge, United Kingdom; [2]UK SuperSTEM Laboratory, Daresbury Laboratory, Daresbury, United Kingdom; [3]National Center for Electron Microscopy, Lawrence Berkeley National Laboratory, Berkeley, California; [4]Department of Chemical Engineering and Materials Science, University of California at Davis, Davis, California.

The wide band-gap semiconductor gallium nitride (GaN) and it's alloys have received tremendous attention in recent years due to its applications in light emitting diodes (LEDs) and laser diodes (LDs) in the blue region of the spectrum. One major area of research involves understanding the influence of the abundant dislocations present in the active layer of devices on the efficiency and reliability of the devices. Of the three types of commonly occurring dislocations, both edge and screw dislocations have been studied extensively. The mixed dislocation - which has a Burgers vector that is a linear combination of the screw and the edge dislocation - has a core structure that has previously eluded both experimental and theoretical analysis due to its complexity. Here we present a detailed study of mixed dislocations in which the intricacies of the atomic arrangement in the cores have been imaged directly using an aberration corrected scanning transmission electron microscope. In addition to being present as a full core structure, the mixed dislocation is observed to dissociate into partial dislocations separated by a stacking fault only a few unit cells in length. The mechanisms of dissociation have been studied, and based on the experimental results, the generation of this stacking fault appears to be impurity driven. Its presence is consistent with longstanding theoretical predictions of the dissociation of mixed dislocations into partial dislocations in materials with hexagonal crystal symmetry.

E8.26
Investigation of the Structure and Optical Properties of High Al Content AlGaN Films Grown by MBE.
Anirban Bhattacharyya[1], R. Chandrasekaran[1], Theodore D. Moustakas[1], Yiyi Wang[2], Ahmet S. Ozcan[2], K. F. Ludwig[2], Zhou Lin[3] and David J. Smith[3]; [1]Electrical and Computer Engineering, Boston University, Boston, Massachusetts; [2]Physics, Boston University, Boston, Massachusetts; [3]Center for Solid State Science and Department of Physics and Astronomy, Arizona State University, Tempe, Arizona.

AlGaN alloys with high AlN mole fraction are under intense investigation for their potential applications in Deep UV emitters and detectors. However for the same composition, these alloys can have different structure and optical properties depending on the kinetics of growth. This is primarily due to complex ordering effects, which have been reported in these alloys [1].In this paper we present a systematic study of the growth by MBE and structural and optical characterization of bulk AlGaN alloys with AlN mole fraction ranging from 70% to 85%. During the growth of these films, kinetic factors such as the ratio of group III to Group V, substrate temperature and level of Si doping, were investigated. The structure and microstructure of the films were investigated by Synchrotron XRD, TEM and SEM. The Optical properties were studied by optical absorption spectroscopy, and CL measurements. Cross-sectional TEM micrographs of films grown under different group-III / Group-V ratios indicate that dislocation density is lowest for films grown under group III/V ratio close to 1.Under these conditions, the majority of the dislocations are of the threading type, and they annihilate rapidly with increasing film thickness. XRD as well as TEM results show that the films exhibit complex chemical ordering phenomena, and the film grown under group V-rich condition show the highest degree of ordering. We find that the degree and the type of ordering depend strongly on the growth conditions and doping levels. AlGaN films grown either under Group-III or group-V rich conditions show extensive band tailing in their optical absorption spectrum consistent with higher concentration of defects and complex ordering. On the contrary films grown under Group III / Group V ratio close to 1, show a sharp absorption edge. Correspondingly, CL data on films grown both under group-III and under group V-rich conditions exhibit strong sub bandgap luminescence, while the ones grown under Group III/V ratio 1 show primarily band-gap luminescence. Thus under optimized conditions, we have obtained films with 85 % AlN mole fraction that exhibit a sharp CL peak at 240nm at RT, with the ratio of band-edge luminescence to sub bandgap luminescence of more than 500:1. [1] E. Iliopoulos, K. F. Ludwig, Jr., T. D. Moustakas, and S. N. G. Chu , Appl. Phys. Lett. 78, 463 (2001)

E8.27
Abstract Withdrawn

E8.28
P-Type GaN Epitaxial Layers and AlGaN/GaN Heterostructures with High Hole Concentration and Mobility Grown by HVPE. Alexander Usikov[1,2], Oleg Kovalenkov[1], Vladimir Ivantsov[1], Vladimir Dmitriev[1], Natalia Shmidt[2], Dmitrii

Poloskin[2], Vladimir Petrov[2] and Valentin Ratnikov[2]; [1]Technologies and Devices International, Silver Spring, Maryland; [2]A.F. Ioffe Physico-Technical Institute of Russian Academy of Sciences, St.-Petersburg, Russian Federation.

One of the major technical issues in the development and manufacturing of GaN-based light emitting devices and electronic bipolar devices is a p-type doping. In this paper we report on novel results on highly doped p-type GaN layers and AlGaN/GaN heterostructures grown by hydride vapor phase epitaxy (HVPE) on sapphire substrates. For Mg doped GaN layers, hole mobility as high as 80 cm2V-1s-1 and hole concentrations ranging from 1*1018 to 3*1018 cm-3 was measured using conventional van der Pau Hall effect technique at room temperature. P-type GaN layers with electrical resistivity of 0.02 Ohm cm were fabricated. Temperature dependencies of carrier concentrations and mobility were measured and will be presented. Thickness of GaN layers ranged from 2 to 5 microns. Both as-grown and annealed layers have high mobility and carrier concentrations, however the highest numbers were measured for annealed samples. Typically, annealing procedure at 750oC in argon ambient results in increasing of the Na-Nd concentration in 1.5-3.5 times. As HVPE is well-known 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 also will report on initial results obtained on highly electrically conducting p-type GaN and AlGaN/GaN heterostructures doped with Zn. Concentration Na-Nd in the 1017 - 1018 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 low background impurity concentration in GaN layers grown by HVPE, typically providing materials with concentrations Nd-Na from high 1014 cm-3 to low 1015 cm-3 range. Results of material characterizations performed for p-type doped layers and structures using SIMS, x-ray diffraction, and AFM will be presented.

E8.29
Abstract Withdrawn

E8.30
Impact of H_2-Preannealing of Sapphire Substrate on Crystallization of Low-Temperature-Deposited AlN Buffer Layer. Michinobu Tsuda[1,2], Motoaki Iwaya[2], Satoshi Kamiyama[2], Hiroshi Amano[2] and Isamu Akasaki[2]; [1]Single Crystal Division, Kyocera Corporation, Youkaichi, Shiga, Japan; [2]Faculty of Science & Technology, 21st Century COE "Nano-Factory", Meijo University, Nagoya, Aichi, Japan.

Success in the growth of device-quality GaN on a 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 H_2 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 GaN epilayer, otherwise, polycrystalline GaN is grown. In this paper, the effect of H_2-preannealing on the crystalline quality of the LT-buffer layer, which is in direct contact with the sapphire surface, 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 H_2-preannealing is performed for 5 min at three different annealing temperatures, T_a = 400, 900 and 1,200°C, before the deposition of the LT-AlN layer. As-deposited LT-AlN layers and LT-AlN layers which are annealed at 1,050°C, which is the growth temperature of GaN, are compared. The LT-AlN 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 $2\theta/\omega$ scan of the LT-AlN layers deposited on the substrates with different T_a values, in the case of the as-deposited layers, none of the diffraction peaks is observed when T_a = 400°C. A relatively weak diffraction peak is observed when T_a = 900°C, and a markedly strong peak is observed when T_a = 1,200°C. Peak position is lower than 36°. In the case of the annealed LT-AlN layers, no peaks appear when T_a = 400°C, and the peak intensities at T_a = 900 and 1,200°C become stronger than those of the as-deposited layers. The peak positions of these layers are shifted to approximately 36.0°, which indicates the existence of free-standing AlN. It is noted that the crystallinity of a LT-AlN layer, characterized on the basis of XRD pattern, shows a significant difference when T_a is varied. On a sapphire substrate preannealed at a low T_a, a LT-AlN layer with poor crystallinity (or an amorphous layer) is deposited. In the case that T_a is sufficiently high, the as-deposited LT-AlN layer is crystallized. However, the lattice is strained by the effect 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 H_2-preannealing is crucial for the quality of a LT-AlN layer and the subsequently grown GaN epi-layer.

E8.31
Low Frequency Noise Characterization In AlGaN/GaN HEMTs With Varying Gate Recess Depth.
Shrawan Kumar Jha[1], B. H. Leung[1], Charles Surya[1], H. Schweizer[2] and M. H. Pilkhuhn[2]; [1]Electronic & Information Engineering, Polytechnic University of HongKong, Kowloon, Hong Kong; [2]Department of Physics, University of Stuttgart, Stuttgart, Germany.

Low frequency noise measurements were performed on a number of AlGaN/GaN HEMT devices with different gate recess depths, which were formed by dry etching. In addition, further noise characterization were done after stressing the devices for more than 200 hours at V_{DS} = 10 V and V_G = 1.5 V, while the room temperature noise was monitored time to time after every stressing session. At room temperature, the voltage noise power spectral density, $S_v(f)$ were found to show $1/f$ dependence in all devices irrespective of recess depth. A comparison of noise level in these noise power spectral density spectra clearly indicate increase in the noise levels for the devices with large recess depth, reflecting the degradation caused by ion-impact induced damage during recess formation. The results of stress measurements showed earlier degradation of the device with higher gate recess depth further confirming the effect of dry etching induced damage in gate recess and hence indicating the need and importance of a better etching process for gate recess formation in such devices.

E8.32
Growth and Physics of GaN-Based Wrinkled Quantum Wells by MBE. Jasper S. Cabalu[1], Christos Thomidis[1], Theodore D. Moustakas[1] and Spilios Riyopoulus[2]; [1]Electrical and Computer Engineering, Boston University, Boston, Massachusetts; [2]Science Applications International Corporation, McLean, Virginia.

The development of efficient and low-cost GaN-based light emitting diodes (LEDs) for blue/ultraviolet (UV) light sources has been an area of intense research over the past several years, with a goal towards producing light sources for solid-state white lighting. Two of the greatest challenges facing such efforts are (a) the quantum efficiency for light generation and (b) the light extraction efficiency from the LED. Due to these challenges, the current overall power conversion efficiency of nitride LEDs is 21%. In this paper, we report on the growth and optical properties of wrinkled quantum wells grown by plasma-assisted molecular beam epitaxy (PAMBE) on spontaneously formed GaN textured templates. The intension is to develop the active region of an LED structure having an improved internal quantum efficiency and high extraction efficiency. GaN smooth and textured templates, auto-doped n-type, have been grown by the halide vapor-phase epitaxy (HVPE) method. These GaN templates were characterized by studying their reflectivity in the UV and visible parts of the spectrum as well as their photoluminescence (PL) excited with a He-Cd laser. We find that the reflectivity of the textured templates is suppressed to approximately 1% to 2% in the entire spectral region. Identical 20 pairs of GaN/AlGaN MQWs, with well and barrier widths of 8 nm, were grown on both the textured and the smooth GaN templates by plasma-assisted MBE and their optical properties were evaluated by photoluminescence (PL) and cathodoluminescence (CL) measurements. The PL spectra of the smooth MQWs and the multiple wrinkled quantum wells (MWQWs) have significant differences. The PL from the smooth quantum wells has a single peak at 384 nm consistent with the expected red-shift due to the quantum confined stark effect since the QWs were grown along the [0001] polar direction. The PL peak MWQWs occurs at 358 nm, which is consistent with QWs having a square configuration. Furthermore, we found that the integrated photoluminescence intensity from the MWQWs was more than 100 times than that of the smooth MQWs. We attribute this significant enhancement of the photoluminescence from the MWQWs partly to enhanced light extraction through the textured surface, which is expected to be only 4% from the smooth surface, and partly to enhanced spontaneous emission rate. We believe that the increase in the internal quantum efficiency is due to the reduction of the quantum confined Stark effect since the quantum wells are not perpendicular to polar [0001] direction. Further enhancement is expected due to quantum carrier confinement from "wedge" electronic eigen-modes. A theoretical model describing the enhancement in the extraction efficiency and the enhancement in the spontaneous emission from the wrinkled quantum well structures will also be presented.

E8.33
The Influence of Stacking Faults on the Optical Properties of GaN. Jin Mei[1], Sridhar Srinivasan[1], Rong Liu[1], Fernando A. Ponce[1], Takashi Mukai[2] and Shinji Tanaka[2]; [1]Dept. Physics and Astronomy,

Arizona State University, Tempe, Arizona; [2]Nichia Corporation, Anan, Tokushima, Japan.

Low temperature luminescence of GaN sometimes exhibits a peak at 364nm (3.42eV). 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]. In this study we have established a direct correlation between microstructure and the 364nm emission using TEM and cathodoluminescence (CL) spectroscopy. The study was carried out on GaN grown by epitaxial lateral overgrowth (ELOG). To provide a precise correlation, cross-section TEM samples were made using standard preparation procedures. Before TEM observation, liquid helium temperature CL measurements were performed. Monochromatic CL images show that the 364nm luminescence is specifically confined to the lateral overgrowth region above the SiO_2 mask. Using the same TEM samples, two-beam diffraction condition imaging was used to study the microstructure. Stacking faults were observed in the same regions of 364nm CL emission and vice versa. This result is the first to directly correlate the presence of stacking faults to the 364nm emission from GaN. The nature of stacking faults has been analyzed using different diffraction conditions. Stacking faults on a-planes have been observed at jogs 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).

E8.34
Influence of Substrate Misorientation Angle and Direction in Molecular-Beam Epitaxial Growth of GaN on Off-Axis SiC (0001). Jun Suda[1,2], Yuki Nakano[1] and Tsunenobu Kimoto[1]; [1]Dept of Electronics Science and Engineering, Kyoto University, Kyoto, Japan; [2]PRESTO, 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 SiC homoepitaxial growth (necessary to fabricate the SiC active region) is at present established only on off-axis substrates, the III-N semiconductor must be grown on off-axis SiC. We have investigated growth of AlN and GaN on off-axis SiC substrates. Roughening of the surface after III-N growth 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 with various misorientation angles to understand this phenomenon. GaN layers were grown by molecular-beam epitaxy using elemental Ga and active nitrogen generated by an EPI unibulb rf-plasma source. First, we have tried 4H-SiC (0001) 8°-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 detailed analysis of the surface morphology, 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 results in reduction of the peak-to-valley height to 3 nm. However, the surface still has the same undulating features (on a smaller length scale). On the other hand such morphology was not observed for GaN grown on (0001) on-axis SiC substrates (misorientation $< 0.3°$). We investigated various misorientation angles and directions. The critical misorientation angle and direction at which the surface roughening disappears will be discussed.

E8.35
Abstract Withdrawn

E8.36
Molecular Beam Epitaxy of GaN on Lattice-matched ZrB_2 Substrates Using Low Temperature GaN and AlN Nucleation Layers. Rob Armitage[1], Kazuhiro Nishizono[2], Jun Suda[1] and Tsunenobu Kimoto[1]; [1]Kyoto University, Kyoto, Japan; [2]Kyocera Corporation, Kyoto, Japan.

ZrB_2 is an interesting substrate for (Al)GaN due to its closely matched in-plane lattice constant and thermal expansion coefficient. For some applications the high electrical and thermal conductivities of ZrB_2 are also advantages. However a two-step method must be used due to poor wetting, and the lack of crystal polarity of ZrB_2 may complicate efforts to control the polarity of the III-nitride epilayer. In this work we study the influence of low-temperature GaN (LT-GaN) and AlN nucleation layers on polarity and epitaxial quality of GaN grown on ZrB_2 by rf-MBE. LT-GaN nucleation layers result in nitrogen polarity. Both the morphology and defect density of the GaN main layer are sensitive to the LT-GaN Ga/N ratio. For slightly N-rich nucleation the RHEED becomes spotty, but streaks are restored with initiation of high-temperature GaN growth. In contrast for slightly Ga-rich LT-GaN nucleation the RHEED remains streaky throughout growth. Slightly N-rich nucleation leads to a very smooth main layer morphology with straight atomic steps up to several μm in length (rms 0.5 nm over 10 μm). For slightly Ga-rich nucleation the dislocation density is lower, but the morphology is less smooth. The atomic step length is shorter (sub-μm) and there are height variations of 5-10 nm between adjacent sub-grains of size 1 μm. Typical x-ray ω scan widths are 7 and 12 arcmin, respectively, for the (0002) and (1-104) peaks for slightly Ga-rich nucleation, and 14 and 19 arcmin for slightly N-rich nucleation. The only features in the low-temperature photoluminescence spectra of GaN main layers grown with LT-GaN nucleation layers are the donor-bound exciton peak and phonon replicas. The D_0X peak has a width of 10 meV at 18 K, and appears at 3.473 eV indicating a nearly strain-free crystal, consistent with the good thermal and lattice match of ZrB_2. AlN nucleation layers lead to either Ga- or N-polar GaN main layers depending on the AlN thickness and deposition parameters. Since GaN is more closely lattice matched to ZrB_2 than AlN, the AlN nucleation layer should ideally be psuedomorphic, i.e. very thin. For nucleation at 550 C an AlN layer as thin as 1 nm can yield Ga-polarity, while at 700 C an AlN layer thicker than 2 nm is necessary to ensure Ga-polarity. Ga-polar films exhibit the spiral hillock morphology. The AlN nucleation process has not been optimized and the preliminary structural quality is inferior to that obtained with the LT-GaN process. While the present epilayers are much improved compared to earlier attempts at MBE growth on ZrB_2, the dislocation density remains unexpectedly high given that the initial nucleation appears to be 2D. Additional characterization of thin (<10 nm) GaN nucleation layers and the GaN/ZrB_2 interface is now underway to identify the origin of the high dislocation density. Further growth experiments are also in progress using exactly lattice-matched $Al_{0.24}Ga_{0.76}N$ layers.

E8.37
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 mostly used as acceptors in order to enable to make the p-type GaN [1]. However, Mg has larger ionization energy compared to any other acceptors and is 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. Moreover, at high Mg concentration, the surfaces 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 [3]. The purpose in this research is to clarify the relationship between the morphology of the film surfaces and defects and to optimize the concentration of Mg in p-type GaN, which its electrical properties are improved. Transmission electron microscopy is also additionally used to investigate microstructural defects. [1] L. T. Romano, M. Kneissl, J. E. northrup, C. G. Van de Walle, and D. W. Treat, Appl. Phys. Lett. 79, 2734 (2001). [2] C. G. Van de Walle, C. Stampfl, J. Neugebauer, J. Cryst Growth, 189/190, 505 (1998). [3] M. Hansen, L. F. Chen, S. H. Lim, S .P. DenBaars, and J.S. Speck, Appl. Phys. Lett. 80, 2469 (2002).

E8.38
In-situ Monitoring of Growth Parameters during Epitaxial Growth of AlN. David Bliss[1], Vladimir Tassev[2], David Weyburne[1], Sheng-Qi Wang[2], Mitchell Fait[1], Jeffrey Anthis[3], Nam Nguyen[3], Michael Suscavage[1], Chris Santeufemio[1] and John Bailey[2]; [1]Air Force Research Laboratory, Hanscom AFB, Massachusetts; [2]Solid State Scientific Corporation, Hollis, New Hampshire; [3]Epichem, 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−alkyl amine adduct with a known vapor pressure and decomposition temperature. This chemical compound possesses relatively high vapor pressure of about

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 gas flows and adduct temperatures shows the relationship between growth rate and the source gas composition. The mass flow of source gas is monitored by measuring its strong UV absorption at about 220 nm. The deposition rate is monitored during growth by the reflection of interference fringes from the film surface using a He-Ne laser beam. Maximal and optimal growth rates of 15 and 10 μm/h, respectively, have been established. HVTE layers have been grown with growth rates 3 to 15 μm/h on 2-inch diameter sapphire wafers. However, it is observed that the growth rate diminishes with time, due to parasitic reactions. The degree of parasitic reactions is determined during the process by the change in transmission of the laser beam due to deposits on the quartz tube. The convective flow issues such as the distance from the nozzle to the substrate, the temperature gradient and flow rates are found to influence the deposition to a greater extent than diffusion, as had been assumed at the outset.

E8.39

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

GaN nanocolumns with GaN/AlN short period superlattice (SL) layer were successively 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 indicated the growth of high quality GaN/AlN SL nanocolumns. The GaN/AlN hetero-junction with a large conduction band offset (∼2eV) is an attractive combination for various quantum effect devices such as ultrafast intersubband transition (ISBT) modulator at optical communication wavelength, 1.55μm quantum cascade laser, resonant tunneling diodes and so on. While the high density of threading dislocations and large lattice mismatch between GaN and AlN brings distortion at the hetero-interfaces. To avoid this problem, we proposed nanocolumns for large lattice-mismatch system. Because the nano-columns are almost dislocation free and small diameter and large aspect ratio, nanocolumn may prevent the interface distortion and clacks of large strain system. In this study, two kinds of GaN/AlN SL nanocolumns with different SL structure (sample A and B) were grown by a 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 (100periods) and GaN (300nm). From the SEM observation, nanocolumns was grown with an average diameter, height and density of ∼100nm, 900nm and $1\sim2x10^{10}cm^{-2}$, 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 under 325nm He-Cd laser irradiation. Strong emission peak was observed for both samples. The peak wavelength was 380nm for sample A and 430nm for sample B and the peak intensity was about 5∼10 times stronger than that of conventional MOCVD grown non-dope GaN layer with a dislocation density of 5.5 x $10^9cm^{-2}$and thickness of 3.75μm. The theoretically calculated peak wavelength of AlN/GaN samples considering polarization field are agreed well with experimental value. These results suggest that GaN/AlN superlattice nanocolumns is an attractive candidate for various quantum effect devices. This work was supported by a NEDO Industrial Technology Research Grant #02A23041d and Grant-in-Aid for Scientific Research (A) #14205057 from the Ministry of Education, Culture, Sports and Technology.

E8.40

Dislocation Reduction in GaN Epilayers by Maskless Pendeo-Epitaxy Process. Dong Jun Park[1], Jeong Yong Lee[1], Hyung Koun Cho[2], Chang Hee Hong[2], and Hung Seob Cheong[3]; [1]Materials Science and Engineering, Korea Advanced Institute of Science and Engineering, Daejeon, South Korea, [2]Metallurgical Engineering, Dong-A University, Busan, South Korea, [3]Semiconductor Science and Technology, Chonbuk National University, Chonju, 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 layers had been successfully grown on c-plane sapphire substrates in spite of large lattice mismatch (13 %) and the difference of thermal coefficiency. But the dislocation density in the GaN films grown on sapphire substrates has the range from 10^8 to $10^{10}/cm^2$. Especially, most of threading dislocation propagates along the growth direction and destroys the active layer, which are believed to deteriorate the optical and transport properties. The representative techniques designed for the reduction of threading dislocation are epitaxial lateral overgrowth (ELO) and Pendeo-epitaxy (PE). PE is overgrowth technique in which the stripes and/or other seed forms are etched through the nitride material and into the substrate. GaN films were again grown either laterally or vertically over a mask. However, the growth fronts over the masked region were tilted. It was found that thermally induced stress and mask materials were presumed to affect tiling behavior. The degree of crystallographic tilt in dielectric mask-removed PE GaN layers was found to be reduced due to the elimination of the interface between dielectric masks and laterally grown GaN layers. It was found that two-step PE growth of GaN is a useful technique to improve crystalline quality of the PE GaN through facet control. It is based on the control of GaN structures by changing growth conditions during the PE process. In this paper, we investigated dependence of the maskless PE GaN structure to the growth temperatures via LP-MOCVD for the stripe mask patterns. And crystalline property and anisotropy of PE GaN are characterized. Based on the knowledge of the change in the GaN facet structure, typical two kinds of two-step growth techniques of GaN are demonstrated and the distribution of the threading dislocations are investigated by TEM.

E8.41

Time-Resolved Photoluminescence Studies of Eu^{3+} Centers in GaN. Hong Ying Peng[1], Henry O. Everitt[1], Chang-Won Lee[1], J. M. Zavada[2], D. S. Lee[3], and A. J. Steckl[3]; [1]Department of Physics, Duke University, Durham, NC; [2]US Army Research Office, Research Triangle Park, NC; [3]Nanoelectronics 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 Eu^{3+} 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 ($^5D_0 \rightarrow {}^7F_2$) from GaN:Eu as a function of pump energy. Strong absorption occurs at pump energies above the GaN band-gap, while a broad impurity band is observed below the band edge. Optical excitation into this impurity band reveals a weaker but otherwise characteristic red luminescence from the Eu^{3+} ions, suggesting that a complex of Eu-related and native defects exist that permit energy transfer from the host and impurity bands to the $^5D_0$ state of Eu^{3+}. Pump wavelength-dependent TRPL revealed that photoexcitation at the I_2 bound exciton exhibits temperature-independent energy transfer, while photoexcitation at other energies activates additional temperature-sensitive pathways. These results are anticipated to be ubiquitous in the RE-doped GaN system and may reconcile recent inconsistent reports of thermal quenching when the role of differing photoexcitation energies are reexamined. The cw PL measurements clearly indicate two classes of light-emitting transitions in GaN:Eu: ones that luminesce for photoexcitation just below the GaN band gap and others that do not. PLE measurements indicate a broad absorption tail extending 550 meV below the GaN band gap for the former transitions (type I) while indicating no below-gap absorption tail for the latter transitions (type II). Based on the splitting of $^5D_0 \rightarrow {}^7F_0$ transition and its dependence on excitation energy, three Eu^{3+} centers can be claimed of type I nature, while two other Eu^{3+} centers are of type II nature. Using wavelength-tunable femtosecond pulsed laser excitation and a streak camera operated in photon-counting mode, all allowed emission lines and transition decays from each of the $^5D_2$, $^5D_1$ and $^5D_0$ upper levels to the ^7F_J (J=0,1,2,3) lower levels have been measured. The corresponding assignments have been attempted within a wide spectrum range between 450nm and 700nm mainly from their TRPL decay behavior. The systematic energy levels could be used to simulate the crystal field parameters of Eu^{3+} ions in GaN. Biexponential fitting of the emission decay shows that the $^5D_2 \rightarrow {}^7F_J$ and $^5D_1 \rightarrow {}^7F_J$ transitions for all five Eu^{3+} centers have a similar fast and slow decay constant of 0.5ms and 5 ms, much faster than the $^5D_0 \rightarrow {}^7F_J$ transitions with a typical value of 30ms and 180 ms.

E8.42

TEM Analysis of Reduction of Dislocation Density in AlGaN Grown on an AlN Template. Noriyuki Kuwano[1], M. Haraguchi[2], A. Ishiga[3], H. Miyake[3], K. Hiramatsu[3], and T. Shibata[3,4]; [1]ASTEC, Kyushu University, Kasuga, Fukuoka, Japan; [2]Dept Adv Sci for Electr Mater, Kyushu University, Kasuga, Fukuoka, Japan; [3]Dept Elec Electr, Mie University, Tsu, Mie, Japan; [4]NGK Insulators Ltd, Nagoya, Aichi, Japan.

Growth of good quality AlGaN layers with high Al contents is very essential for fabrication of light emitting/detecting devices for deep

ultraviolet wavelength regions. We reported previously that a pure GaN layer with few threading dislocations (TDs) can be grown successfully on an AlN template, but that in the case of AlGaN layers, many TDs in the AlN template penetrate upwards. In the present work, various types of AlN templates were used to reduce the density of TDs in the AlGaN layers. Transmission electron microscope (TEM) observation was performed to analyze the behavior of TDs in order to seek the optimum condition for reduction of TD density. We used two types of AlN templates: (1) The surface of AlN template was carved by lithography to have sloped planes. (2) The rugged AlN template was grown so that it has many small facets on the. An Al1-x Ga_x N (x=0.5) layer was grown by low-pressure MOVPE on these AlN templates. TEM specimens were prepared with a focused ion beam (FIB) mill. Observation was carried out with JEM-2000EX and Tecnai-G2-F20. In the specimen of type-1 (sloped plane), TDs in the AlN template penetrate into the AlGaN, bending toward the direction normal to the interface between AlGaN/AlN. The dislocation density on the top surface of AlGaN then has fluctuation according to the shape of the interface. The dislocation density was estimated to be approximately 10^8 cm $^{-2}$ in the lower areas. In the specimen of type-2, the AlN template was found to have a columnar structure: Dislocations in the AlN template were concentrated to form grain boundaries, so that there were few TDs inside the columnar crystals. Since the AlGaN layer was grown in the way of lateral-over-growth, dislocations on the grain boundaries do not penetrate into the AlGaN layer. The dislocation density in the AlGaN was reduced to be $10^8 cm^{-2}$ or less.

SESSION E9: New Directions in Nitride Research
Chairs: Oliver Ambacher and Alexey Kavokin
Thursday Morning, December 2, 2004
Back Bay C (Sheraton)

8:30 AM *E9.1
Spintronics in Nitrides. Tomasz Dietl, Institute of Physics, Polish Academy of Sciences, Warszawa, Poland.

Semiconductor spintronics aim in developing material systems, in which novel mechanisms of control over magnetization in magnetic compounds and over individual spins in semiconductor nanostructures could lead to new functionalities in classical and quantum information hardware, respectively [1]. The talk will present a survey of theoretical and experimental works, in which the unique properties of group III nitrides are exploited in both contexts mentioned above. In particular, the report of progress in understanding of magnetism in the nitrides doped with transition metals and rare earth elements will be given emphasizing contradictory opinions concerning basics characteristics of these materials. The actual position of magnetic impurities in the GaN lattice as well as a possible role of structural and electronic phase separation will be discussed. The question whether the hole introduced by the Mn impurities is localized tightly on the Mn d-levels or rather on the hybridized p-d bonding states will be addressed. The nature of spin-spin interactions and magnetic phases, as provided by theoretical and experimental findings, will be outlined, and possible origins of high and low temperature ferromagnetism observed in these systems will be presented. It is known that weak spin decoherence and strong spin-spin coupling are required to fabricate functional quantum gates of semiconductor quantum dots. Owing to the weakness of spin-orbit interactions, especially long spin life times are to be expected in nitrides. Recent weak localization studies of nitrides aiming at evaluation of phase coherence time down to millikelvin temperature range will be discussed together with time-resolved Faraday rotation that has been used to measure electron spin coherence in n-type GaN epilayers [2]. Despite large densities of charged threading dislocations, this coherence yields spin lifetimes of about 20 ns at T = 5 K, and persists to room temperature. Importantly, this low decoherence rate is coupled in GaN with a small value of the dielectric constant. This will enhance characteristic energy scales for quantum dot charging as well as for the exchange interaction of the electrons residing on the neighboring dots. [1] For reviews, see, e.g., T. Dietl and H. Ohno, MRS Bulletin, October 2003, p. 714. [2] B. Beschoten et al., Phys. Rev. B 63 (2001) 121202. The work is supported by FENIKS project (EC G5RD-CT-2001-00535) within 5th Framework Programme of European Commission

9:00 AM E9.2
Evidence of Carrier Mediated Ferromagnetism in GaN:Mn/GaN:Mg Heterostructures. Erdem F. Arkun[1], Mason J. Reed[1], Acar E. Berkman[1], Nadia El-Masry[1], Meredith L. Reed[3], John Zavada[2] and Salah M. Bedair[3]; [1]Materials Science and Engineering, North Carolina State University, Raleigh, North Carolina; [2]Army Research Office, Durham, North Carolina; [3]Electrical and Computer Engineering, North Carolina State University, Raleigh, North Carolina.

Dilute Magnetic Semiconductors (DMS's) possess a strong potential to make use of the spin of carriers in spintronic devices. Experimental results and theoretical calculations predict that GaN:Mn is a prominent semiconductor material for spintronic device applications. 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 demonstrated. 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. Additionally, it is demonstrated 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 DHS that exhibits room temperature ferromagnetism is grown. An identical structure, with the exception of insertion of an AlGaN barrier in order to obstruct the carrier transfer at the interface, results in paramagnetic films for AlGaN barriers thicker than 25nm. These results are explained based on the change in the occupancy of the 3d-Mn impurity band, and indicate that carrier mediation 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 E9.3
Synthesis and Properties of GaxMn1-xN films. Rong Zhang, Physics, Nanjing University, Nanjing, China.

R. Zhang, Y. Y. Yu, X. Q. Xiu, Z. L. Xie, S. L .Gu, B. Shen, Y. Shi, and Y. D. Zheng Jiangsu Provincial Key Laboratory of Photonic and Electronic Materials 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-Tc up to 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, Mn-doped GaN films on HVPE-grown GaN substrate were prepared using HVPE technique. 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 in a horizontal HVPE (Hydride 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 850oC with liquid Ga and Mn, respectively, while N2 gas was used as carrier gas. NH3 gas was used as N source. A 1um-thick HVPE-GaN layer was used as substrate for epitaxy of Mn-doped GaN films. The growth temperature is 1050oC. A 4um thick layer was grown on HVPE-GaN substrate after 15 minutes growth. X-ray diffraction and x-ray photoelectron energy spectroscopy measurements indicate that GaxMn1-xN films have been synthesized with x up to 0.16. The lattice constant of the epilayers increases with the Mn composition. AFM characterization implies that Rms (root-mean-square) roughness is in the scale of nm order. Raman scattering measurements indicate that the phonon frequencies of E2 (low), E2 (high), A1(TO)and A1(LO) modes of HVPE-grown GaN are 144, 567, 533 ,and 734 cm-1 respectively. For the Mn-doped sample, there are some obvious differences compared with the undoped GaN sample. First, two broaden bands come forth centered at 302 cm-1 and 674 cm-1. We contribute attribute to disorder-activated scattering, which means that built-in defects and crystal disorder cause a relaxation of the selection rules for first-order Raman scattering and phonons from the whole Brillouin zone can be observed in the Raman spectrum. Second, a new peak arises at wave numbers of 589 cm-1. We deem that the 589 cm-1 peaks were contributed to local vibrations of Mn ions in GaN lattice 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 redshif can be attributed to strain but not variety of charge carrier concentration. VSM measurements show obvious hysteresis loops at room temperature, indicating that the films are ferromagnetic at room temperature. M-T measurements give the Curie temperature is as high as 350K. The mechanism of ferromagnetism of Mn-doped GaN films will be discussed.

9:30 AM E9.4
Impact of Manganese Incorporation on the Structural and Magnetic Properties of MOCVD-Grown $Ga_{1-x}Mn_xN$.
Matthew H. Kane[1,2], Ali Asghar[1], Hun Kang[1], Adam M. Payne[1], Ian T. Ferguson[1], Christopher R. Summers[2], Christy R. Vestal[3], Z. John Zhang[3], Martin Strassburg[1,4], Jayantha Senawiratne[4], Nikolaus Dietz[4], Dmitry Azamat[5], Wolfgang Gehlhoff[5], Ute Haboeck[5] and Axel Hoffmann[5]; [1]School of Electrical and Computer Engineering, Georgia Tech, Atlanta, Georgia; [2]School of Materials Science and Engineering, Georgia Institute of Technology, Atlanta, Georgia; [3]School of Chemistry and Biochemistry, Georgia Institute of

Technology, Atlanta, Georgia; [4]Department of Pysics and Astronomy, Georgia State University, Atlanta, Georgia; [5]Institut fuer Festkoerperphysik, Technische Universitaet Berlin, Berlin, Germany.

We report on the metal-organic vapor phase epitaxy (MOCVD) growth and the impact of the Mn incorporation on the structural, optical and magnetic properties of GaMnN. High-quality epitaxial films of varying thickness and manganese doping levels were grown by introducing Bis-cyclopentadienyl manganese (Cp2Mn) into a chemical hower head reactor during the GaN growth. Crystalline quality and phase purity were determined by high-resolution 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 layer of 3.30 Å. A uniform Mn concentration is confirmed by secondary ion mass 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 pronounced compensation in the MOCVD-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. Therefore, an unambiguous identification of the impurity center is provided. The isotropic g factor and the isotropic hyperfine parameter A are identical with the values found for Mn-doped GaN-films grown by molecular beam epitaxy (MBE). The determined fine-structure parameter D corresponds to values found for almost relaxed GaN-MBE films. Despite the preferential incorporation of manganese as Mn2+, room temperature ferromagnetism was found for samples with a manganese concentration of 0.5 %. SQUID measurements showed an apparent ferromagnetic hysteresis. None of the requirements for room temperature ferromagnetism in the prevailing mean field DMS theories were found. Therefore, different origins of the ferromagnetic signal are discussed. A nanocluster Mn-rich phase model of ferromagnetism similar to that postulated for MOCVD grown InMnAs epilayers 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 hole from the Mn3+ state into the valence band.

9:45 AM E9.5
Optical and Structural Investigations on Mn Ion States in MOCVD-grown $Ga_{1-x}Mn_xN$. Martin Strassburg[1,2], Jayantha Senawiratne[1], Nikolaus Dietz[1], Matthew H. Kane[2], Ali Asghar[2], Adam M. Payne[2], Ian T. Ferguson[2], Christopher R. Summers[3], Ute Haboeck[4], Axel Hoffmann[4], Dmitry Azamat[4] and Wolfgang Gehlhoff[4]; [1]Department of Physics and Astronomy, Georgia State University, Atlanta, Georgia; [2]School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, Georgia; [3]School of Materials Science and Engineering, Georgia Institute of Technology, Atlanta, Georgia; [4]Institut 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 $Ga_{1-x}Mn_xN$. Since the Mn2+ 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 MOCVD grown $Ga_{1-x}Mn_xN$ (x 0.005) epilayers with thickness ranging from 0.2 μm to 1 μm are reported. The incorporation and the electronic structure of the manganese ions were studied by ESR. Resonances according to the 36 hyperfine structure states were observed. These observed resonance patterns are well described by the spin Hamiltonian for isolated 55Mn2+ centers providing an unambiguously identification of the impurity center. The isotropic g factor and the isotropic hyperfine parameter A are identical with the values found for Mn-doped GaN-films grown by molecular beam epitaxy (MBE) [1]. According to observed linewidths in the ESR spectra and the determined fine-structure parameter D = 0.024 cm^{-1} the presence of significant strain in the epilayers was ruled out. This was confirmed by micro-Raman investigations. The E2 high and the A1 (LO) Raman mode were found at 567 cm^{-1} and 734 cm^{-1}, respectively. These values are in good agreement with those measured for relaxed GaN revealing that no additional strain was introduced although the high concentration of manganese ions (10^{20} cm^{-3}). A high carrier concentration (above 10^{18} cm^{-3}) was ruled out since not broadening of the A1 mode and no LPP modes were detected. The lack of a higher concentration of free carriers is attributed to the compensation of the Mn acceptors by crystal defects and native impurities acting as shallow donors. Such mechanisms are known to hamper strong p-type doping in wide bandgap semiconductors, and are reported for GaN:Mg. The identification of compensation mechanisms and the determination of their levels are facilitated by photoluminescence and absorption spectroscopy. At room temperature, a broad emission band ranging from 2.7 eV to 3.1 eV was observed in the as-grown samples indicating pronounced compensation in the MOCVD-grown GaMnN epilayers. Most of these defects were removed by annealing. In addition, an absorption band around 1.8 eV was observed that is assigned to the emission of a hole from the Mn3+ state into the valence band [2]. The position of the Fermi level and the hence, a possible presence of a Mn4+ state, recently reported by Han et al. [3] for co-doped GaMnN:Mg epilayers, is investigated by NIR spectroscopy. 1 T. Graf et al., Phys. Rev. B67, 165215 (2003). 2 T. Graf et al., APL 81, 5159 (2002). 3 B. Han et al., APL 84, 5320 (2004).

10:30 AM *E9.6
Site Multiplicity of Rare Earth Ions in III-Nitride Hosts.
Kevin Peter O'Donnell, Viatcheslav Katchkanov and Renibel Network; Physics, University of Strathclyde, Glasgow, United Kingdom.

III-nitride epilayers doped with rare-earth (RE) ions have attracted significant attention recently due to their possible exploitation in light emitting devices [1]. In particular, emission of red, green and blue light can be achieved by doping III-N with Eu, Er and Tm, respectively [2]. Intra-f-shell transitions in free space are forbidden by electric-dipole selection rules. It is therefore of considerable importance to establish the lattice location of RE in solid hosts, since a lowering of the local symmetry is thought to strongly enhance the transition probability for favourable sites. This talk summarises evidence obtained to date for the existence of site multiplicity of RE 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 (average) 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, p 97 (2001) [2] M.J. Garter and A.J. Steckl, IEEE Transactions on Electron Devices 49, p 48 (2002)

11:00 AM E9.7
Optical activation of implanted Eu ions in AlN-capped GaN.
Robert W. Martin[1], Iman S. Roqan[1], Ke Wang[1], Uli Wahl[2], Katherina Lorenz[2], Eduardo Alves[2], Stephane Dalmasso[1], Kevin P. O'Donnell[1], Sandra Ruffenach[3], Olivier Briot[3] and Renibel Network[1]; [1]Physics Department, Strathclyde University, Glasgow, United Kingdom; [2]ITN, 2686-953 Sacavem, Portugal; [3]GES, Universite de Montpellier II, 34095 Montpellier, France.

The doping of GaN with optically active rare earth ions provides an alternative route to the development of integrated, all-nitride light-emitting devices for several applications in display technology. In this study europium (Eu) ions were implanted into GaN epilayers capped with thin epitaxially grown layers of AlN. The cap is shown to circumvent the two main disadvantages associated with conventional ion-implantation; namely the limited repair of lattice damage at low annealing temperatures and the formation of an amorphous layer at the surface. The repair of lattice damage is promoted by annealing at very high temperatures, in excess of 1000 deg. C for GaN, which usually results in thermal dissociation of the material. Employing the thin (< 10 nm) AlN cap is shown to protect the sample during this post-implant high temperature annealing and also to prevent the formation of an amorphous surface layer during the implantation. For low implantation fluences (up to 1e15 at/cm2) no dissociation of the crystal was observed by Rutherford backscattering and channeling (RBS/C) measurements for annealing temperatures up to 1300 deg. C. Remarkably, the intensity of the Eu-related luminescence, as measured by cathodoluminescence at room temperature, increases by one order of magnitude within the studied annealing range between 1100 and 1300 deg. C. For implantation fluences larger than 2e15 at/cm2 the dissociation of GaN and an out-diffusion of the implanted rare earth ions is observed with RBS/C for annealing at 1300 deg. C. SEM and AFM imaging indicate that annealing temperatures exceeding 1300 deg. C induce blisters within the protective cap which are likely to be related to explosive dissociation of the underlying GaN. The RE-related luminescence remains intense despite this aggressive treatment.

11:15 AM E9.8
Aquamarine Luminescence Band in Undoped GaN.
Michael A. Reshchikov[1,2], Lei He[2], Richard J. Molnar[3], S. S. Park[4], K. Y. Lee[4] and Hadis Morkoc[2,1]; [1]Physics, Virginia Commonwealth University, Richmond, Virginia; [2]Electrical Engineering, Virginia Commonwealth University, Richmond, Virginia; [3]Lincoln Laboratory, Massachsetts Institute of Technology, Lexington, Massachusetts; [4]SAIT, Suwon, South Korea.

We report a new defect-related photoluminescence (PL) band in undoped GaN. The 1-2 μm-thick GaN layers were grown by molecular beam epitaxy on top of a 10 μm-thick GaN buffer layer which in turn was grown on sapphire or 200 μm-thick freestanding template prepared by hydride vapor phase epitaxy. The aquamarine luminescence (AL) band appeared as a broad band with a maximum at 2.55−2.56 eV at low temperatures. With increasing temperature, the AL band broadens, 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 AL band at low excitation intensities. Although the shape and the peak position of the AL band are close to the characteristics of the green luminescence band in a freestanding GaN template [1], we distinguish these two bands for their markedly different behavior with temperature and excitation intensity. We will present the results of a detailed study of the AL band and growth conditions favoring its appearance in GaN. The origin of defects responsible for this PL band remains unknown. [1] M. A. Reshchikov, H. Morkoc, S. S. Park, and K. Y. Lee, Appl. Phys. Lett. 81, 4970 (2002).

11:30 AM E9.9
Heterojunction Band Offset Measurements of the ZnO-GaN Interface. Charles Fulton[1], R. J. Nemanich[2,1], C. Liu[3], Sang-Jun Cho[3] and H. Morkoc[3]; [1]Materials Science & Engineering, North Carolina State Univ, Raleigh, North Carolina; [2]Physics, North Carolina State Univ, Raleigh, North Carolina; [3]Electrical Engineering & Physics, Virginia Commonwealth Univ., Richmond, Virginia.

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 epitaxial layers were prepared by MBE on unintentially doped GaN films grown on sapphire substrates. The N-face GaN layer was grown on top of a GaN buffer layer on sapphire 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 $\pm$ 0.1 and 1.05 $\pm$ 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 are 1.95 and 1.15 eV, respectively. The interface dipole 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 bonding.

11:45 AM E9.10
The interaction of defects and hydrogen in proton-irradiated GaN(Mg,H). Carleton H. Seager[1] and Sam M. Myers[2]; [1]01111, Sandia National Laboratories, Albuquerque, New Mexico; [2]01112, Sandia National Laboratories, Albuquerque, New Mexico.

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 concentration, 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 grown-in protium (H) or deuterium (D) 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 (9 cm-1) higher in energy. Roughly coincident 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 anneals at 800°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 elevated temperature behavior. The new, slightly shifted infrared absorption is ascribed to the migration of a point defect, probably the N interstitial, into the vicinity of the Mg-H complex. 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.

SESSION E10: Lasers and Light-Emitting Diodes II
Chairs: Kevin P. O'Donnell and Shigetaka Tomiya
Thursday Afternoon, December 2, 2004
Back Bay C (Sheraton)

1:30 PM *E10.1
Advances in AlGaN-based Deep-UV LEDs. Mary H. Crawford, Andrew A. Allerman, Arthur J. Fischer, Katherine H. A. Bogart, Stephen R. Lee, Weng W. Chow, Sebastian M. Wieczorek, Robert J. Kaplar and Steven R. Kurtz; Sandia National Labs, Albuquerque, New Mexico.

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 a compact, robust, wavelength tailorable, milliwatt-level deep-UV source that could replace mercury lamps and similar UV sources. These applications include fluorescence-based biological agent detection, water purification, sterilization and decontamination, non-line-of-sight communications and thin film curing. While most near-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 alloys 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 > 1e10 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 metal-organic 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 spectra. Electroluminescence at wavelengths shorter than 240 nm will be presented, and limitations in short wavelength performance will be discussed. Sandia is a multiprogram laboratory operated by Sandia Corporation for the United States Department of Energy's National Nuclear Security Administration under Contract DE-AC04-94AL85000. This work is supported by DARPA under the SUVOS program.

2:00 PM *E10.2
Homo- and Heteroepitaxy for GaN-Based Laser Diodes. S. Figge, T. Boettcher, J. Dennemarck, S. Einfeldt, C. Roder and D. Hommel; Institute 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 $1/cm^2$. Sapphire has in comparison to GaN a worser thermal conductivity and therefore the heat accumulation in the device derogates the performance of heteroepitaxially grown devices to a larger extend. Homoepitaxy 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 homoepitaxy 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 wavguide structures.

The influence of process parameters during chemical assisted ion beam etching and subsequent crystalographic wet etching on the quality of the end mirrors will be discussed. Electro-optical data obtained from LD structures grown on sapphire and GaN substrates reveal an improved performance of devices grown on GaN substrates. Calculations on the thermal resistance show a three times better heat conductivity on GaN substrates and are in good agreement with experimential data. 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 are able to give an analytical description of the thermal 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 experimential data like wafer curvature and fracture toughness of HVPE grown layer on sapphire.

2:30 PM E10.3
Development of LED Structures for General Illumination.
David Brackin Nicol[1], Ali Asghar[1], Dhairya Mehta[1], My Tran[1], Hun Kang[1], Ian T. Ferguson[1], Mustafa Alevli[2], Jayantha Senawiratne[2], Christoph Hums[2,3], Martin Strassburg[2], Nikolaus Dietz[2] and Axel Hoffmann[3]; [1]Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, Georgia; [2]Department of Physics and Astronomy, Georgia State University, Atlanta, Georgia; [3]Institute of Solid State Physics, Technical University of Berlin, Berlin, Germany.

A series of GaInN/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 employed as useful feedback tool. Using scratch diodes and fabricated 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 was 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. The peak obtained by EL was redshifted compared to the peak of the PL emission (e.g., compare: 2.64 eV (470 nm) for EL to 2.67 eV (464 nm) for PL). In order to gain further insight in the mechanisms of light generation, temperature dependent and site selective PL spectroscopy were applied. Localization centers having activation energies of 5 meV and 44 meV, respectively, were revealed from the behavior of the emission intensity. Unlike the typical S-shape in the detected transition energy, no significant shift in the PL peak maximum was observed between 8 K and 295 K. In addition, a decrease of the peak emission energy with decreasing excitation energies was observed using site selective spectroscopy with excitation energies ranging from 3.4 eV to 2.9 eV. The influence of the internal electric fields, microscopic fluctuations of the In concentration and a gradual change in the In concentration in the growth direction strongly influence the localization potential for carriers in the InGaN/GaN MQWs. Their impact on the emission behavior of the LEDs is discussed.

2:45 PM E10.4
Thermal Analysis of Multi-Quantum Well LEDs in InGaN/GaN/Sapphire Structure Using Nematic Liquid Crystal Thermography.
Jeong Park[1], Chin C. Lee[1] and MooWhan Shin[2]; [1]Electrical Engineering and Computer Science, University of California, Irvine, Irvine, California; [2]Department of Materials Science and Engineering, Myong Ji University, Yongin, Kyunggi-Do, South Korea.

The conversion efficiency of lighting LEDs is important device parameter and it degrades significantly as case temperature (Tc) 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 occur. However, the relationship between efficiency and Tj is not available because Tj is unknown during LED operation. In this research, we design a new configuration to measure the LED junction temperatures using nematic liquid crystals with laser illumination. Accurate measurement of junction temperature is necessary to reveal how the conversion efficiency changes with the temperature of the active region. One objective is to investigate the effect of the junction temperature on the electrical and optical performance of LED devices. The nematic liquid crystal thermography method was used to measure the junction temperature of GaN/AlGaN/GaN/Sapphire LEDs. This method is non-destructive and has high spatial resolution limited only by the resolution of the optical microscope. This technique can provide temperature accuracy within +/- 1C. However, in applying this technique to LEDs, great difficulty exists. The LED light during operation would easily overwhelm the illumination light in the existing 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 780nm in wavelength is employed 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 chips. 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 rises from 25C to 107C. The thermal resistance is measured to be 114 C/watt. The peak temperature is found near p-contact, agreeing with fact that this region has the highest current density. With the relationship 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 that the diode can be modeled as an ideal diode in series with a parasitic resistance caused by the p-contact and the current spreader. The ideality factor of the diode is about 4.

3:00 PM E10.5
Nitride LEDs on 6" Si substrates.
Jing Li[1], J.Y. Lin[2] and Hongxing Jiang[2]; [1]III-N Technology, Inc, Manhattan, Kansas; [2]Physics, Kansas State University, Manhattan, Kansas.

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. There have been previous reports on the growth of nitride LEDs on 2" Si substrate and the lattice and thermal mismatch between GaN and Si is known to result in the formation of dislocations and cracks in the grown nitride films. We report here on the nitride growth by MOCVD on 6-inch Si (111) substrates by employing high quality AlN epilayer as a template. Through careful optimization of the growth conditions, we have obtained InGaN/GaN multiple quantum wells (MQWs) LEDs which provide blue and green emission (450 to 500 nm). The successful demonstration of GaN based LEDs on 6" Si substrate provides the possibility for significant reduction in nitride LED price by taking advantages of low cost, large area substrates and mature backside processing/thermal management techniques. This will expand the future prospects of nitrides for a wide range of applications, including solid-state lighting. Unique problems associated with nitride growth on large area Si substrates have been identified. Approaches to reduce dislocation density, wafer bowing, and cracks, as well as to increase quantum efficiency of LEDs on 6" Si substrates have been investigated and will be discussed.

3:30 PM *E10.6
Nitride-Based Light-Emitting Diodes Grown on Particular Substrates: ZrB_2, (30-38) SiC and R-faced Sapphire.
Satoshi Kamiyama, Motoaki Iwaya, Hiroshi Amano and Isamu Akasaki; Faculty of Science and Technology, Meijo University, Nagoya, Japan.

There are many kinds of nitride-based devices ever developed, such as blue, green and near-UV LEDs, violet LD, HEMT and so on. However, all the nitride layers used in commercial devices are grown on lattice-mismatched c-face sapphire or SiC 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 channels in nitride-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 nitride growth with particularly oriented substrate. The unique substrates including ZrB_2, (30-38) 4H-SiC and R-faced sapphire are evaluated for the application to mainly nitride-based light-emitting diodes (LEDs). The ZrB_2 has a hexagonal AlB_2 atomic arrangement, and perfectly lattice-matched to $Al_{0.26}Ga_{0.74}N$. With the other excellent physical properties such as high electrical and thermal conductivities, this substrate material is promising for the application to nitride-based LEDs. The (30-38) 4H-SiC and R-faced 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 under optimized growth conditions, although the FWHMs of XRD for them were broader than that of c-faced 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 R-faced 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 R-faced sapphire, smaller blue shift with increasing injection 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
Reliable and Efficient Homoepitaxially-grown InGaN/GaN Light-emitting Diodes. X. A. Cao, S.D. Arthur, S.F. LeBoeuf, J.M. Teetsov and M.P. D'Evelyn; GE Global Research Center, Niskayuna, New York.

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 diffusion-recombination current dominated at intermediate forward bias, and reverse-bias current was originated from carrier generation and tunneling associated with deep-level traps. Nanoscale electrical characterization using conductive atomic 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 nonradative 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 (28x higher at 500 mA, or 700 A/cm2). 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 E10.8
Reliability and Operation Lifetime Studies of sub-280 nm Ultraviolet Emitters on Sapphire Substrates. Ashay Chitnis, Maxim Shatalov, Shuai Wu, Salih Saygi, Wenhong Sun, Vinod Adivarahan 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 focus towards developing sub-300 nm emission ($\lambda <$ 300 nm) high power deep ultraviolet (UV) emitters to be used in bio-chemical detection and air/water purification etc. Several groups including ours have reported AlGaN-based sub-280 nm deep UV emitters on sapphire substrates. [1,2,3] Recently, we have improved the performance of these light-emitting diodes by employing 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 100μm x 100μm device. For an array of four 100μm x 100μm packaged devices, record cw power of 1.53 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 driven at current injection levels (J >200 A/cm^2) which are close to those of laser diodes. Therefore, device reliability and long term stability emerge as significant issues. To date no reliability data has been reported on sub-280 nm deep UV LEDs. We now present a systematic study of reliability and lifetime measurements of the packaged 280 nm LEDs. Several packaged 100μm x 100μm devices were mounted on a fixture to provide continues bias and a simultaneous measurement of the emitted UV power. The fixture was then placed in a temperature/humidity chamber. Lifetime to 80% (L80) and lifetime to 50% (L50) values were then estimated from room temperature voltage-current-light (I-V-L) measurements. At bias current of 20 mA (J= 200 A/cm^2), L80 of few hours was measured. The L50 value was estimated to be in excess of 100 hours. The failure mechanism in these devices was attributed to degradation of top p-type metallization. We expect to further improve the lifetime/stability of these LEDs by modified contact formation. Details of the study, identification of the degradation mechanism and approaches to further improve the lifetime will be presented. 1. V. Adivarahan, S. Wu, J. P. Zhang, A. Chitnis, M. Shatalov, V. Mandavilli, R. Gaska, M. Asif Khan, Appl. Phys. Lett. 84 4762 (2004). 2. A. J. Fischer, A. A. Allerman, M. H. Crawford, K. H. A. Bogart, S. R. Lee, R. J. Kaplar, W. W. Chow, S. R. Kurtz, K. W. Fullmer, J. J. Figiel, Appl. Phys. Lett. 84 3394 (2004). 3. A. Hanlon, P. M. Pattison, J. F. Kaeding, R. Sharma, P. Fini, S. Nakamura, Jpn. J. Appl. Phys. 42 L628 (2003).

4:30 PM E10.9
Characterization of Minority-Carrier Hole Transport in Nitride-Based Light-Emitting Diodes with Optical and Electrical Time-Resolved Techniques. Robert J. Kaplar, Steven R. Kurtz, Daniel D. Koleske, Andrew A. Allerman, Arthur J. Fischer and Mary H. Crawford; Sandia National Laboratories, Albuquerque, New Mexico.

Transport of massive holes in nitride-based devices such as light-emitting diodes (LEDs) and photodetectors is a critical factor influencing performance. However, majority-carrier Hall mobility measurements overlook the influence of a large density of defects, and minority-carrier transport needs to be investigated directly. Towards this end, we have implemented a new technique that combines measurements of the electrical and optical transient responses of an LED to a forward-to-reverse bias voltage pulse. Using this method, we have observed hole transport in p^+-n quantum well (QW) LEDs where the QW is positioned in the n-region. The devices were grown on sapphire using MOCVD. Hole transport results may depend strongly on growth substrate and conditions. Initially we examined an InGaN/GaN single quantum well (SQW) LED (QW emission $\approx$ 400 nm) designed for this experiment with the SQW located 100 nm from the p^+-n junction. Transient responses of the LED were induced using a transmission-line technique. We observed that both the electrical current and optical emission transients displayed two-step decays, a signature of diffusive behavior. A classic solution to the time-dependent diffusion equation produced a self-consistent description of both optical and electrical data within a narrow range of values for the GaN minority-carrier hole lifetime ($\approx$ 760 ns), diffusion length ($\approx$ 590 nm), and mobility ($\approx$ 0.2 cm^2/Vs). Further, temperature-dependent measurements of the hole mobility indicated that it is thermally activated ($E_\mu \approx$ 50 meV). The magnitude and temperature dependence of the mobility imply that minority hole transport is trap-modulated, and the lifetime is suggestive of slow recombination processes occurring through deep levels. Optical measurements were also performed for two broad sub-bandgap SQW LED emission peaks, centered at $\approx$ 450 nm and $\approx$ 575 nm. The 450 nm peak showed a clear two-step response with a long time constant (approaching the hole lifetime) for the second phase, suggestive of a uniformly distributed luminescence center. In contrast, the 575 nm peak did not show a clear two-step decay, implying a complex luminescence process not directly interpretable in terms of our simple diffusion model. Room-temperature measurements of an $Al_{.15}Ga_{.85}N/Al_{.45}Ga_{.55}N$ multi-quantum-well (MQW) LED (QW emission $\approx$ 300 nm) yielded much longer lifetime ($\tau_p \approx$ 3.0 μs) and shorter hole diffusion length ($L_p \approx$ 280 nm) in $Al_{.45}Ga_{.55}N$. Hole mobility was found to be an order of magnitude lower than in GaN, with $\mu_p \approx 10^{-2}$ cm^2/Vs, and the mobility was found to be insensitive to temperature. These results suggest that hole transport in high-Al-content AlGaN is completely dominated by impurity conduction, with transport possibly occurring by percolation through a high-density network of defects. Sandia is a multiprogram 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. Cabalu[1], Christos Thomidis[1], Anirban Battacharyya[1], Theodore D. Moustakas[1] and Charles Collins[2]; [1]Electrical and Computer Engineering, Boston University, Boston, Massachusetts; [2]U.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-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. Large area mesa devices (800 micron-square) with different geometries were fabricated using conventional optical lithography and were designed for backside light extraction. The LED design took advantage of peripheral n-metal contacts 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 into 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 mode 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 (DC) operation 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 drive current from 336.5 nm to 341 nm, which is attributed to device heating. Packaging of the devices through flip-chip bonding processes 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 Evening, December 2, 2004
8:00 PM
Exhibition Hall D (Hynes)

E11.1
Grain Expansion and Subsequent Seeded Growth of AlN Single Crystals. Dejin Zhuang, Raoul Schlesser and Zlatko Sitar; Materials Science and Engineering, North Carolina State University, Raleigh, North Carolina.

Ongoing efforts of growing large AlN 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 AlN surfaces previously exposed to air. The growth process is based on physical vapor transport (PVT), where AlN powder is sublimed in a high purity nitrogen atmosphere. The growth temperature was typically in the range of 2100 to 2200 °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 AlN 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 and defect–selective etching indicate that the grown crystals have a high crystalline quality and low extended defect density.

E11.2
Optimization of Growth and Activation of Highly Doped p-type GaN for Tunnel Junctions as Buried Current Spreading Layers in Dual Wavelength LEDs for Phosphor Pumping. David Brackin Nicol, Ali Asghar, Edem Wornyo and Ian T. Ferguson; Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, Georgia.

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 1e20 and employed a low growth temperature of less than 1050 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 were also grown using the 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 AlN Bulk Crystals. Balakrishnan Krishnan[1], Motoaki Iwaya[1], Satoshi Kamiyama[1], Hiroshi Amano[1], Isamu Akaskai[1], Takashi Takagi[2] and Tadishi Noro[2]; [1]Materials Science and Engineering (21st Century COE Nano-Factory), Meijo University, Nagoya, Japan; [2]Ceramic 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 obstacle to realizing the full device potential of III nitrides in the fields of opto-electronics and electronics. Successful growth of high quality AlN single crystals will solve this problem to a great extent. We have made an attempt to study the growth kinetics of AlN single crystals by sublimation technique (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 to 2400°C. The system is evacuated to 5 x10^{-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 (0001) oriented 6H-SiC substrates. The single crystalline AlN results in the temperature range of 1970-2100°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 SiC seeded method are 9x6x0.3 mm^3. The best crystal resulted exhibits an XRD omega rocking curve FWHM of 4.81 arcminutes. AlN growth is found to start off with the formation of hexagonal islands. Later, the hexagonal islands, coalesce and form the complete crystal. AlN layers grown on Si-SiC and C-SiC show different growth behaviors. In the micorsocpic 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 AlN layers grown on C-SiC is easier to peel off when compared with the layers grown on Si-SiC. 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 00) as the dominant faces although growth is found to have propagated faster along the c-direction. The crystals are thin (thickness range 7-20μm) and transparent. These crystals grow on the inner walls 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 (#5206001) and Akasaki Research Center, Nagoya University, Naogya, Japan.

E11.4
In-situ Measurements of the Critical Thickness for Strain Relaxation in AlGaN/GaN Heterostructures. Stephen R. Lee[1], Dan Koleske[1], Karen Cross[1], Jerry Floro[1], Karen Waldrip[1], Adam Wise[2] and Subhash Mahajan[2]; [1]Sandia National Laboratories, Albuquerque, New Mexico; [2]Department 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 compositions ranging from x=0.14 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(0.51)Ga(0.49)N layers grown to the critical thickness (11 nm) shows unterminated surface-fracture channels in further support of this interpretation. AFM also shows a marked 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 strains in the underlying thin films, which influences the slip systems initially available for dislocation glide. 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 Corporation, a Lockheed Martin Company, for the United States Department of Energy National Nuclear Security Administration under contract DE-AC04-94AL85000.

E11.5

Resonant and Non-Resonant Micro-Raman Studies of Wide Bandgap Nanopowders. Leah Bergman[1], Xiang-Bai Chen[1], John L. Morrison[1], Jesse Huso[1], Dmitriy Myedvyedyev[1], Heather M. Hoeck[1] and Shlomo Efrima[2]; [1]Physics Department, University of Idaho, Moscow, Idaho; [2]Department of Chemistry, Ben-Gurion University, Beer-Sheva, Israel.

Studies of resonant and non-resonant Raman scattering of AlN and ZnO nanopowders having wurtzite structure with an average size of 80 nm are presented. The wurtzite 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 (5.08 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 mode is the prominent mode and the A1(LO) polar mode is weak when the visible laser lines are utilized. The A1(LO) mode became the stronger mode for UV laser excitation at 325 nm. As for AlN, the E2 mode is found to be the stronger mode for all the laser lines utilized in this experiment. The A1(LO) mode became detectable only for the deep UV excitation at 244 nm. The Raman mode behavior of the ZnO and AlN nanocrystallites is discussed in terms of the Frohlich interaction, absorption length, and resonant and non-resonant Raman selection rules.

E11.6

Direct AFM Observation of Strain Effects on MOCVD Grown GaN Epilayer Surface Morphology. Doru Florescu, J.C. Ramer, V.N. Merai, A. Parekh, D.S. Lee, D. Lu and E.A. Armour; Veeco TurboDisc, Somerset, New Jersey.

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 dynamic simulations, the authors demonstrated that this behavior 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), field effect transistors (FETs), and detectors. To obtain increased brightness from LEDs and LDs, a highly uniform and smooth surface of epitaxial GaN film 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 optical efficiency enhancement of (In, Al)GaN 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 surface morphology dependence on the absolute strain values for thin (<10 microns) epitaxial films grown using a Veeco TurboDisc GaNzilla E300 MOCVD platform on (0001) sapphire. Preliminary results indicate an excellent correlation between the surface roughness observed employing a Veeco DI3100 AFM and epilayer strain values. An overall increase of surface roughness (i.e. decrease of the terrace width) is found with decreasing compressive strain (i.e. epilayer vs. bulk value), which is achieved by employing different nucleation techniques during GaN buffer layer growth. In addition, strain relaxation by typical V-shaped, hexagonal pits is directly observed by comparison of surface features between the pits and neighboring areas of thin epilayer films. The implications of these findings for MOCVD process development and AFM characterization of high power/high brightness commercial applications will be discussed. [1] Y.H. Xie, G.H. Gilmer, C. Roland, P.J. Silverman, S.K. Buratto, J.Y. Cheng, E.A. Fitzgerald, A.R. Kortan, S. Schuppler, M.A. Marcus, and P.H. Citrin, Phys. Rev. Lett. 73, 3006 (1994). [2] E.A. Fitzgerald, S.B. Samavedam, Y.H. Xie, and L.M. Giovane, J. Vac. Sci. Technol. A 15(3), 1048 (1997). [3] J.C. Ramer, D.I. Florescu, D.S. Lee, L. Liu, and E.A. Armour, Proceedings of the 204th ECS Meeting, Orlando, FL, October 12-16, 2003

E11.7

Spectroscopic Ellipsometry Characterization of Amorphous III-V Nitride Thin Films. Jebreel M. Khoshman and Martin E. Kordesch; Physics & Astronomy, Ohio University, Athens, Ohio.

The optical constants and polarized optical properties of amorphous III-V nitride thin films, a−(Al, Ga, In) N, deposited by reactive radio frequency magnetron sputtering onto silicon (111) and glass substrates have been investigated. The optical constants of a−AlN (in the range 200−1400 nm), a−GaN (in the range 300−1400 nm), are obtained by analysis of the measured ellipsometric spectra through the Cauchy−Urbach model while the optical constants of a−InN (in the range 300−1400 nm) is determined using the Tauc−Lorentz model. Refractive indices of a−(Al, Ga, In) N are found to be in the range 1.92 − 2.26, 2.02 − 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 64°, 65°, and 67°. 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.

E11.8

Room-temperature synthesis of ultraviolet-emitting nanocrystalline GaN films using photochemical vapor deposition. Takashi Yatsui[1], Syunsuke Yamazaki[2], Takashi Nagira[2], Motoichi Ohtsu[3,1,2], Tae-Won Kim[4] and Hiroshi Fujioka[3,4]; [1]SORST, JST, Machida, Tokyo, Japan; [2]Interdisciplinary Graduate School of Science and Engineering, Tokyo Institute of Technology, Yokohama, Kanagawa, Japan; [3]Faculty of Engineering, the University of Tokyo, Bunkyo-ku, Tokyo, Japan; [4]Kanagawa Academy of Science and Technolog, Kawasaki, Kanagawa, Japan.

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 NH_3 and the substrate. Hence, the development of low-temperature synthesis of high-quality GaN would allow us not only to fabricate abrupt heterointerfaces between GaN and the substrate but also to reduce the defects due to the difference in the thermal expansion coefficients. Photo-CVD (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/III ratio of nanocrystalline GaN films deposited at RT using PCVD. GaN samples (100-nm thickness) were grown on a sapphire (0001) substrate at RT. We used TMG and semiconductor grade NH_3 as the III and V sources, respectively. $H_2$was used as the carrier gas for the TMG. The partial pressure of NH_3 was fixed at 500 Torr, so the V/III ratio (g) was varied by changing the partial pressure of TMG. We used a frequency-quintupled Q-switched Nd:YAG laser (λ = 213 nm) as the light source for the photodissociation. The PL spectra of the samples were examined using a CW He-Cd laser (λ = 325nm). 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 $\leq$ g $\leq$ 90 show a broad peak with a full width at half maximum (FWHM) of 0.5 eV. It is observed around 3.1 eV for the samples deposited with g $\leq$ 90, 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 $\leq$ 5000. Furthermore, the low temperature (5 K) PL spectra of the samples with g = 50000 and 500000 show two dominant PL peaks at 3.366 and 3.310 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 gallium and nitrogen. The atomic composition ratio of the nitrized gallium was determined using the relative sensitivity factor: gallium, 54.5%; nitrogen, 45.5%. This implies that the deposited film was well nitridized by the PCVD due to the large V/III ratio, even at RT.

E11.9

High-Frequency Generation in Low-Mobility Superlattices. Vladimir Litvinov[1] and Alexander Manasson[2]; [1]WaveBand Corporation, Irvine, California; [2]Department of Applied Physics, University of Michigan, Ann Arbor, Ann Arbor, Michigan.

Millimeter wave oscillations in semiconductor superlattices (SL) is possible due to formation of electrical domains when the superlattice is dc-biased above the critical field. In this case, dc-negative differential conductivity (NDC) induces traveling electrical domains oscillating with the frequency determined by the length of the superlattice and peak drift velocity of the carriers, as described in Ref.[1]. Anticipated THz generation, also in the region where dc-bias is above critical voltage, is based on Bloch oscillations. However,

operation of a true Bloch oscillator (BO) in a continuous wave mode is severely limited by formation of electrical domains resulting from dc-NDC. A strong ac-component of the driving field can suppress 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 GaAs-based superlattices in Refs.[2,3]. 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 ac-force period result in reactive carrier oscillations. We found that the positive dc-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 stable nonlinear media, but due to the instability in the regions where corresponding nonlinear conductivity is negative and dc-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. We emphasize, that in low-mobility superlattices such as GaN/AlGaN, the diffusive regime is the only accessible one with capability of providing terahertz generation. [1] Schomburg, S. Brandl, K. Hofbeck, T. Bloemer, J. Grenzer, A. A. Ignatov, K.F. Renk, D.G. Pevel'ev, Yu. Koschurinov, V. Ustinov, A. Zhukov, A. Kovsh, S. Ivanov, P.S. Kop'ev, "Generation of millimeter waves in GaAs/AlAs superlattice oscillator", Appl. Phys. Lett. 72, 1498 (1998) [2] H. Kroemer, "Large-amplitude oscillation dynamics and domain suppression in a superlattice Bloch oscillator", cond-mat/0009311 (2000) [3] Y. Romanov, L. Mourokh, N. Horing, "Negative high-frequency differential conductivity in semiconductor superlattices", J. Appl. Phys. 93, 4696 (2003).

E11.10

Crystallinity and Polarity of III-V Nitride Semiconductors Grown on ZnO. Takeshi Ohgaki[1], Naoki Ohashi[1], Shigeaki Sugimura[3,1], Isao Sakaguchi[1], Katsumi Maeda[3], Mitsuru Sato[3,2] and Hajime Haneda[1,4]; [1]National Institute for Materials Science, Tsukuba, Japan; [2]NIMSWave Inc., Gunma, Japan; [3]Tokyo Denpa Co.Ltd., Tokyo, Japan; [4]Kyushu University, Fukuoka, Japan.

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 crystallinity of GaN based alloys grown on single crystalline ZnO substrates. We used hydrothermally grown ZnO single crystals as substrates, 10x10 square or 2 inches diameter in size. The subsrates were polished with chemically and mechanically-polising and finally flatten 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 surface. The crystallinity 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 face ZnO substrate with (In,Ga)N 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 crystallinity of GaN films. Thus, it was demonstrated that controlling of polarity of III-V nitride on ZnO was possible by optimizing growth conditions of, particularly, buffer layers. We will also present about high quality InN films grown on ZnO substrates.

E11.11

Optimization of GaN Channel Conductivity in AlGaN/GaN HFET Structures Grown by OMVPE. Seth Martin Hubbard, Dimitris Pavlidis, E. Cho, G. Zhao and W. Sutton; University of Michigan, Ann Arbor, Michigan.

Semi-insulating GaN templates are necessary for electronic devices in order to ensure drain-source current saturation, complete channel pinch-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. We have focused this paper on tuning the insulating properties of OMVPE grown GaN by adjusting only the final growth temperature and nucleation layer (NL) thickness. Using optimum temperature and NL, we have achieved sheet resistance of 10^{10} Ω/sq, comparable to that of Fe-doped GaN. In addition, we have investigated the subsequent impact of the higher dislocation density present in the semi-insulating GaN on typical AlGaN/GaN HFET material, electrical and device properties. Low-pressure OMVPE was used to grow a series of 2 μm thick layers of GaN on sapphire substrates. We have used a two-step growth process with a 15-40 nm GaN NL deposited at 530° C and the main GaN layers grown between 1005-1045° C. Samples with both 26 nm and 30 nm NL thickness were grown with main growth temperature between 1005° and 1045° C. In either case, the in-situ reflectance recovery time correlated inversely to the growth temperature, with higher growth temperature leading to shorter recovery time. Both NL 26 and 30 nm thickness show a peak sheet resistance at 1033° C. In order to see the effects of the NL thickness, the growth temperature was also fixed at 1033° C and the NL was varied between 15-40 nm. The best results were seen for the 26 nm NL thickness at 1033° C, giving a sheet resistance of 10^{10} Ω/sq. The XRD measurements for both 26 nm and 30 nm NL thickness samples show a steady increase in the (10*2) FWHM was increasing temperature, indicating higher edge dislocation density at higher growth temperatures. The above experiments lead to the conclusion that the final growth temperature and NL thickness are critical parameters effecting 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 evaluation of expected sheet resistance and material quality. Both low resistance and high resistance GaN templates were used to grow $Al_{0.3}Ga_{0.7}N$/GaN HFET structures with a nominal 25 nm barrier thickness. The room temperature mobility of the low and high resistive samples was 1260 and 1330 cm^2/Vs, respectively (sheet charge was 1×10^{13} cm^{-2} for both samples). X-Ray Reflectivity gave interface roughness of the low and high channel resistance HFET structures as 11$\AA$ and 7$\AA$, 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 Lepkowski[1] and Jacek A. Majewski[2]; [1]Unipress, High Pressure Research Center, Polish Academy of Sciences, Warszawa, Poland; [2]Walter Schottky Institute, Technische Universitat 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). Nevertheless, there are circumstances where this simple approach is insufficient. Nonlinear elastic properties of GaAs and InAs have recently attracted significant attention. Frogley et al. proposed that pressure dependences of elastic constants in GaAs and InAs are required to explain anomalously small pressure coefficient of band-gap in strained InGaAs 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, C33 in wurtzite phase for all studied nitrides. Much weaker dependences on pressure have 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 ( ) 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 model based on 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 InN and GaN decisively increases the agreement between theoretical 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.Downes, and D.J.Dunstan, Phys. Rev. B 62,13612,(2000) [2] S.W.Ellaway and D.A.Faux, J. Appl. Phys., 92,3027,(2002) [3] G.Kresse and J.Furthmuller, Phys. Rev. B 54, 11169,(1996) [4] T.Suski, H.Teisseyre, S.P.Lepkowski, P.Perlin, T.Kitamura, Y.Ishida, H.Okumura, S.F. Chichibu, Appl. Phys. Lett. 81,232,(2000)

E11.14

Modeling of elastic, piezoelectric and optical properties of vertically correlated GaN/AlN quantum dots.

Slawomir Pawel Lepkowski[1,3], Grzegorz Jurczak[2], Pawel Dluzewski[2]

and Tadeusz Suski[1]; [1]Unipress, High Pressure Research Center, Polish Academy of Sciences, Warszawa, Poland; [2]Institute of Fundamental Technological Research, Polish Academy of Sciences, Warszawa, Poland; [3]Faculty of Mathematics and Sciences, Cardinal Stefan Wyszynski University, Warszawa, Poland.

Recently, self-organized GaN/AlN or InGaN/GaN QDs, stacked in multilayers, have been considered as a new candidate for the active region in blue or UV light emitters. A strong vertical ordering along the (0001) direction observed in the multilayers of wurtzite GaN/AlN QDs is attributed to a local lattice distortion enhancement localized directly above the previously buried QD [1]. In this paper we theoretically investigate elastic, piezoelectric and optical properties of wurtzite GaN/AlN, hexagonal pyramid-shape QDs, stacked in the multilayers. We have developed a model, based fully on the finite element method, which accurately determines strain distribution, piezoelectric fields and electronic states in wurtzite QDs of arbitrary shape. The model starts from solving the boundary-value problem using the nonlinear theory of anisotropic hyperelasticity based upon the general strain measure [2]. Calculated strain field is used to determine piezoelectric polarization. The spontaneous polarization is taken into account. The distribution of the electrostatic potential is obtained by solving the Poisson equation. The electronic states are calculated using 8x8 kxp hamiltonian of the wurtzite crystal. We perform calculations in two steps. First, we calculate the stress and strain distribution, the piezoelectric fields and the electrostatic potential for the sequence of five GaN/AlN QDs placed one on another in the direction of growth. Second, for the centrally located QD, we calculated electronic states. This procedure allows us to examine the correlations of strain and piezoelectric fields between QDs in the multilayers. Calculations have been performed for structures having different height of QDs and different thickness of the AlN spacers. We observe that the magnitude of the strain in the plane perpendicular to the direction of growth increases in the QDs and decreases in the spacers with increase of the thickness of the spacer. Electric field in the QD increases with the increasing the thickness of the spacer although the difference in piezoelectric polarizations between the QD and the spacer does not change significantly. This effect may be explained using an analogy to the case of GaN/AlN superlattices in which the electric field in the GaN QWs is proportional to the thickness of the AlN barriers [3]. The increase of the electric field in the QD results in the increase of the red-shift of the energy emission. We predict that the energy emission for 4nm height QDs and separated by 10nm-thick AlN layers exhibits a red-shift as large as 200 meV comparing to the energy emission for the same QDs grown with the 5nm-thick AlN spacers. [1] N.Gogneau, F.Fossard, E.Monroy, S.Monnoye, H.Mank, B.Daudin, Appl. Phys.Lett., 84, 4224, (2004) [2] P.Dluzewski, G.Maciejewski, G.Jurczak, S.Kret, J.Y.Laval, Comp.Mat.Sci.,29,379,(2004) [3] V.Fiorentini, F.Bernardini, F.Della Sala, A.Di Carlo, P.Lugli,Phys. Rev. B,60,88

E11.15
Abstract Withdrawn

E11.16
Predicted behavior of the N vacancy in p-type GaN(Mg,H) at elevated temperatures. Samuel M. Myers and Alan F. Wright; Sandia National Laboratories, Albuquerque, New Mexico.

We have modeled the equilibrium thermodynamics and reaction kinetics of the N vacancy (VN), Mg, and H in p-type GaN at elevated temperatures using stable-state and saddle-point energies from density-functional theory (DFT). Our results indicate a large influence of VN compensation on p-type doping, in accord with a growing consensus among investigators; reveal significant dependences upon processing conditions; and illuminate a variety of previous experimental observations. DFT with the generalized-gradient approximation (GGA) for exchange and correlation was applied to nine bound H complexes involving either VN or both VN and Mg, and the results were combined with our previously reported DFT-GGA findings for 19 configurations of isolated H+ and the Mg-H and Mg-VN complexes. Equilibrium populations of these species under Ga-rich and N-rich conditions were computed for the temperature range 500 - 1100 C, taking into account the temperature dependences of the Gibbs free energies of Ga, N2, and GaN. Lower-temperature bounds for the more significant reactions were estimated using H and VN diffusion barriers from our earlier studies, together with a new treatment of the saddle points leading to H trapping within the N vacancy, where electrostatic repulsion is involved. Significant features of the modeling results include the high degree of acceptor compensation that can arise under equilibrium conditions; its strong dependence on the composition and pressure of the ambient; and a lessened suppression of VN formation by H2 ambients due to the formation of highly stable VN-H and Mg-VN-H complexes. This work was supported by the Office of Basic Energy Sciences, US DOE. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

E11.17
Scanning probe investigation of surface charge and surface potential of GaN-lateral polarity heterostructures. Brian J. Rodriguez[1], Alexei Gruverman[2], Woochul Yang[1] and Robert J. Nemanich[1]; [1]Physics, North Carolina State University, Raleigh, North Carolina; [2]Materials Science and Engineering, North Carolina State University, Raleigh, North Carolina.

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 heterostructure (LPH) was evaluated by determining the tip bias that equalized the electrostatic force due to both polar faces. The 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. Michinobu Tsuda[1,2], Masahiro Jimbo[2], Yoshikazu Hirose[2], Motoaki Iwaya[2], Satoshi Kamiyama[2], Hiroshi Amano[2] and Isamu Akasaki[2]; [1]Single Crystal Division, Kyocera Corporation, Youkaichi, Shiga, Japan; [2]Faculty of Science & Technology, 21st Century COE "Nano-Factory", Meijo University, Nagoya, Aichi, Japan.

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 undoed AlGaN-barrier shows low leakage current but shows poor Ohmic property. We found that this controversy can be overwhelmed by using superlattcies as the barrier layers. $Al_{0.3}Ga_{0.7}N$/GaN-SLs with different barrier/well thicknesses are grown on GaN/LT-AlN/sapphire by MOVPE. Modulation doped structures are also grown. X-ray diffraction reciprocal space mapping analysis reveals that the $Al_{0.3}Ga_{0.7}N$/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 $Al_{0.3}Ga_{0.7}N$ (7nm/7nm)-5SLs barrier. Schottky and Ohmic contacts are formed on top layer of the SLs using Ni/Au 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 resistivity is drastically decreased while leakage current is kept small. A HEMT structure having modulation doped $Al_{0.3}Ga_{0.7}N$:Si/GaN SL is fabricated. It exhibits the good pinch-off property. the maximum transconductance is 74mS/mm with gate length and width of 3 and 150 μm, respectively.

E11.19
Compositional Ordering in InxGa1-xN and its Influence on Optical Properties. Zuzanna Liliental-Weber[1], D.N. Zakharov[1], K. M. Yu[1], J. Wu[1,2], S. X. Li[1,2], J.W. Ager III[1], Wladek Walukiewicz[1], E.E. Haller[1,2], H. Lu[3] and W. J. Schaff[3]; [1]Materials Science Division, Lawrence Berkeley National Laboratory, Berkeley, California; [2]Materials Science and Engineering, University of California, Berkeley, California; [3]Department of Electrical and Computer Engineering, Cornell University, Ithaca, New York.

Transmission Electron Microscopy (TEM) and optical measurements on number of In1-xGaxN films ($0 < x < 0.6$) grown by Molecular Beam Epitaxy on sapphire substrates will be presented. Dislocation densities in the InGaN layers were slightly lower than those in the underlying GaN buffer layers and were typically in the mid-$10\hat{1}0$ cm^2 range. Edge dislocations were the most prevalent. In addition to the presence of threading dislocations two types of domain boundaries on (0001) and (01-10) planes were observed in samples with x=0.6. Under certain growth conditions and with x=0.5 compositional ordering along (01-11) planes could be clearly seen which resulted in superlattice reflections in the electron diffraction pattern. 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 In could preferentially accumulate on these polar planes. The relationship between stru c tural properties, compositional ordering, and optical properties of the In1-xGaxN 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. De partment 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 Shahedipour-Sandvik[1], James Grandusky[1], Christopher Keimel[2], Azar Alizadeh[2], Surya Ganti[2], Seth T. Taylor[2] and Steven F. LeBoeuf[2]; [1]School of NanoSciences and NanoEngineering, UAlbany-SUNY, Albany, New York; [2]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 openings (through the SiO2 layer) with a 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, pressure and time), the growth mechanism 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 shape structures, while growth on strained substrates such as sapphire gives rise to sub micron prismatic GaN islands. The morphology, crystallography 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 case), 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 Shwoebel length (l=exp(Es/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. Yoga Saripalli[1], X.-Q Liu[1], J.K. Markell[1], D.W. Barlage[2], M.A.L. Johnson[1] and W.D. Braddock[3]; [1]Material Science and Engineering, North Carolina State University, Raleigh, North Carolina; [2]Electrical and Computer Engineering, North Carolina State University, Raleigh, North Carolina; [3]OSEMI Inc., Rochester, Minnesota.

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 crystallographic 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 results are related to device 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 unpinned 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
Abstract Withdrawn

E11.23
Fabrication of Silicon Nitride Film using Pure Nitrogen Plasma Generated near Atmospheric Pressure for III-V Semiconductor Fabrication. Ryoma Hayakawa[1], Mari Nakae[1], Takeshi Yoshimura[1], Hiroya Kitahata[2], Tsuyoshi Uehara[2] and Norifumi Fujimura[1]; [1]Department of Applied Materials Science, Graduate School of Engineering, Osaka Prefecture University, Sakai, Osaka, Japan; [2]Sekisui Chemical Co., Ltd., Tukuba, Ibaragi, Japan.

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. 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. The reactivity of the excited nitrogen species with Si using nitrogen plasma near atmospheric pressure is also discussed. At 500 Torr, nitrogen plasma was generated by applying alternative pulse with a voltage of 3 kV, a frequency of 30 kHz, and a pulse width of 5 μsec between two parallel plate electrodes at a fixed flow (10 l/min) of high-purity nitrogen (99.9999 %). From optical emission spectroscopy, strong emissions from the N_2 2^{nd} positive series and weak emissions from N_2 Herman/s infrared series were observed. This indicates that the N_2 ($C^3\pi_u$) 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 from 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 1.6 nm at the substrate temperature as low as 25 °C. This supports that the N_2 ($C^3\pi_u$) state should play an important role for the high reactivity with Si like excited atomic nitrogen. From these results, we find great possibility to fabricate high qualitative nitride semiconductor at lower temperature by using this nitrogen plasma.

E11.24
Structure of Misfit Dislocations Resulting from Non-Basal Plane Slip in InGaN/GaN Heterostructures. Rong Liu[1], S. Srinivasan[1], J. Mei[1], F. A. Ponce[1], T. Mukai[2] and Shinji Tanaka[2]; [1]Dept. of Physics and Astronomy, Arizona State University, Tempe, Arizona; [2]Nichia Corporation, 491 Oka, Kaminaka, Anan, Tokushima 774-8601, Japan.

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 100nm In0.17Ga0.83N film grown by MOVPE on GaN free-standing substrate (with a threading dislocation density 10$\tilde{7}$ cm$\hat{}$2). Arrays of misfit dislocations distributed in a six-fold symmetry are observed at the heterojunction interface. The dislocation lines are approximately parallel to directions. Electron diffraction contrast analysis indicates that the Burgers vector component on the basal plane is parallel to the a-vector and perpendicular to the dislocation lines. 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[1], S. Srinivasan[1], J. Mei[1], F. A. Ponce[1], T. Mukai[2] and Shinji Tanaka[2]; [1]Dept. of Physics and Astronomy, Arizona State University, Tempe, Arizona; [2]Nichia Corporation, 491 Oka, Kaminaka, Anan, Tokushima 774-8601, Japan.

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 composition of 0.11, corresponding to 1% lattice mismatch. A large density of surface pits associated with the threading dislocations is observed. These pits nucleate in the GaN substrate and propagate into the InGaN layer. The presence of these pits creates inclined facets in the InGaN/GaN heterostructure, which facilitate the injection of dislocations from the free surface into the strained interface. Under the influence of the lattice mismatch stress, the dislocations can then glide along the basal plane radially outwards from the pit. This produces an interesting flower-shaped dislocation pattern that consists of six sets of dislocation half loops oriented along <11-20> directions. The Burgers vectors of the dislocations is 1/3<11-20>. The distance to which the dislocations propagate depends on the balance of the misfit strain energy and dislocation line tension. This situation creates an interesting laboratory for studying the dynamics of misfit dislocation interaction in the wurtzite nitride semiconductors.

E11.26
Intrinsic Stress Evolution During the MOCVD Growth of GaN on (111) Si Using Graded AlGaN Buffer Layers.
Srinivasan Raghavan and Joan M. Redwing; Materials Science and Engineering and Materials Research Institute, The Pennsylvania State University, University Park, Pennsylvania.

A common problem encountered in GaN growth on Si substrates is crack formation resulting from residual tensile film stress. Prior studies have reported that film cracking can be reduced in micron-thick layers by employing a compositionally graded AlGaN 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 AlGaN 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 (1100oC) based on thermal expansion mismatches. When composition grading was stopped during the compressive segment and growth of a constant composition AlGaN 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 AlN 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 μm thick GaN layers on AlGaN layers >1 μm in thickness was significantly lower than in GaN layers on an AlN 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

E11.28
Study on the Effects of Silicon Doping on the Nanostructures of InGaN/GaN Quantum Wells with Strain-state Analysis.
Meng-Ku Chen[2], Jiun-Yang Chen[2], Cheng-Ming Wu[1], Yung-Chen Cheng[1], Chih-Chung Yang[1], Andreas Rosenauer[3] and Kung-Jen Ma[4]; [1]Institute of Electro-Optical Eng., National Taiwan University, Taipei, Taiwan; [2]Graduate Institute of Electronics Engineering, National Taiwan University, Taipei, Taiwan; [3]Laboratorium for Elektronenmikroskopie, Karlsruhe University, Karlsruhe, Germany; [4]Department of Mechanical Engineering, Chung Hua University, Taipei, Taiwan.

With optical studies, it has been shown that different doping conditions, including different doping layers, in InGaN/GaN quantum-well (QW) structures lead to different nano-structures and hence different optical characteristics. In particular, due to the large lattice mismatch between InN and GaN, indium-rich clusters are usually formed in such a QW structure through spinodal decomposition. In some situations, quantum-dot-like nano-structures can be observed. With different silicon doping conditions, the clustering structures are different. In this paper, we use the strain-state analysis (SSA) method for studying the nano-structures of InGaN/GaN QWs of different doping conditions. We compare 10 samples of different average indium contents, different doping layers (including un-doped, well-doped, and barrier-doped), and different doping concentrations. The SSA method is based on a two-beam interference technique in transmission electron microscopy. The high-quality atomic-scale sample images are then analyzed for the strain mapping and hence the indium concentration distribution based on the Vegard law. Generally speaking, in either the set of low-indium or the set of high-indium samples, compared with the un-doped sample, well doping can usually increase the cluster density within the QWs. Barrier doping leads to the strongest clustering behavior, resulting in island-by-island structures. Therefore, carrier localization is expected to be the strongest for the highest radiative efficiency in the barrier-doped samples. In other words, the QW structures are essentially preserved in the un-doped and well-doped samples. 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 the SSA images, we calculate the average 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 efficiencies under different doping and hence strain conditions.

E11.29
The Critical Height for Dislocation Annihilation and Recombination in GaN Columns Deposited by Patterned Growth.
Mark E. Twigg[1], Nabil D. Bassim[1], Charles R. Eddy[2], Richard L. Henry[2], Ronald T. Holm[2] and Michael A. Mastro[2]; [1]Code 6812, Naval Research Laboratory, Washington, District of Columbia; [2]Code 6882, Naval Research Laboratory, Washington, District of Columbia.

Vertical conduction 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 make an impact in power electronics and high performance UV detection technologies. In particular, the reverse leakage current density will have to drop significantly under large negative biases. In an effort to address this need, we have used MOCVD to grow a patterned array of hexagonal GaN columns on masked heteroepitaxial GaN templates layers using a-plane sapphire substrates. In addition to eliminating cracking (columns heights up to 7 microns have been achieved), we have found that for GaN columns tens of microns in diameter and several microns high, the dislocation density is also significantly reduced (by an order of magnitude to the mid 1E8/cm2 range). Observations using cross-sectional transmission electron microscopy (XTEM) of specimens prepared by focused ion beam (FIB) milling indicate that enhanced dislocation combination and annihilation begins at the growth interface between the hexagonal column and the surface of the template layer. In order to better 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, thus 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 approach similar to that developed by Matthews and Blakeslee for defining the critical thickness in heteroepitaxial layers. Among the predictions of this 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 on a film 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.

E11.30
Vibrational Entropy-Induced Ordering Predicted in the System $Al_{1-X}Ga_XN$.
Benjamin Paul Burton[1] and Axel van de Walle[2]; [1]CTCMS, NIST, Gaithersburg, Maryland; [2]Materials Science and Engineering, Northwestern University, Evanston, Illinois.

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 31 wurtzite-derived supercells. 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 consolute temperature, $T_C \approx 290$K. Including S_{Vib}, one predicts an ordered phase based on $AlGaN_2$ stoichiometry with: 1) a eutectoid temperature, $T_E \approx$ 50K, below which AlN-rich and GaN-rich alloys coexist; 2) a critical temperature for disordering, $T_C \approx 225$K at X=1/5 (this number is highly uncertain, i.e.$\pm$30K); 3)

an undetermined crystal structure. Sharply peaked miscibility gaps between the $AlGaN_2$ phase and the AlN-rich and GaN-rich phases suggest that the phase diagram also has trictitical points at {X≈0.3,T≈140K} and {X≈0.7,T≈140K}.

E11.31

Group III Nitrides Grown on 4H-SiC (30-38) Substrates by Metal-Organic Vapor Phase Epitaxy. Akira Honshio[1], Tsukasa Kitano[1], Masataka Imura[1], Yasuto Miyake[1], Hideki Kasugai[1], Motoaki Iwaya[1], Satoshi Kamiyama[1], Hiroshi Amano[1], Isamu Akasaki[1], Hiroyuki Kinoshita[2] and Hiromu Shiomi[2]; [1]Faculty of Science and Technology, and 21st-Century COE Program "Nano-factory", Meijo University, Nagoya, Japan; [2]SiXON Ltd., Kyoto, Japan.

Although high-efficiency nitride-based light-emitting devices in the visible short-wavelength range have been achieved using strained GaInN quantum wells (QWs), they still have several problems such as a strong internal electric field caused by piezoelectricity. To date, most of these QWs are grown on (0001) GaN. The large piezoelectric field in the QWs causes the quantum-confined Stark effect, resulting in a redshift of the transition energy and a decrease in transition probability. In this report, we propose a new approach to reduce the internal electric field, that is, the use of a 4H-SiC (30-38) substrate. The (30-38) surface of 4H-SiC is tilted 54.7° from the (0001) plane toward the <10-10> direction, and has a similar atomic arrangement to Si (001). GaN layers were grown on 4H-SiC (30-38) substrates by metal-organic vapor phase epitaxy. Sets of GaN samples were grown at different reactor pressures on a (30-38) 4H-SiC substrate covered with a 0.1-μm-thick AlN buffer layer. According to X-ray diffraction measurements, the following two types of crystallographic orientation in GaN layers were found: case (1), the GaN axis is exactly aligned with that of a (30-38) SiC substrate; case (2), the [0001] axis of GaN is inclined 7.4° from the growth direction. Therefore, a reduction in piezoelectricity cannot be expected. In case (2), [0001] SiC is parallel to [10-11] GaN. These two orientations can be controlled by changing the reactor pressure. High-pressure growth promotes case (1), while low-pressure growth promotes case (2). Both GaN layers have specular surfaces as confirmed by SEM observation. The FWHMs of X-ray rocking curves for GaN (0002) and (11-20) diffraction in case (1) are 820 arcsec and 800 arcsec, respectively. On the other hand, in case (2), the FWHMs are 980 arcsec and 504 arcsec, respectively. We fabricated a violet-light-emitting diode with a GaInN-MQW active layer grown on the SiC (30-38) substrate with case (1) orientation. The electroluminescence was measured from the top through a semitransparent Ni/Au contact. The peak wavelength was approximately 420.5 nm, and the FWHM was 25 nm at the injection current of 20 mA. A blue shift of the peak wavelength with increasing injection current of up to 100 mA in this device was smaller than that in the conventional LED on the c-face SiC substrate by a factor of two. This may be due to the smaller internal field. Therefore, GaN-based heterostructures on 4H-SiC (30-38) substrates are very promising for use in high-efficiency light-emitting devices with a weak internal field.

E11.32

Electroluminescence from GaInN Quantum Wells Grown on Non-(0001) Facets of Selectively Grown GaN Stipes. Barbara Neubert[1], Frank Habel[1], Peter Brueckner[1], Martin Schirra[2], Klaus Thonke[2] and Ferdinand Scholz[1]; [1]Optoelectronics, University of Ulm, Ulm, Germany; [2]Semiconductor Physics, University of Ulm, Ulm, Germany.

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 GaInN 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 have studied the optoelectronic properties of GaInN quantum wells grown on such other crystal planes, realised on side facets of selectively grown GaN stipes. We used a low pressure metal organic vapor phase epitaxy system (MOVPE) with a horizontal reactor. A GaN template on c-plane sapphire was stuctured with SiO_2 stripes oriented along the <11-20> and <1-100> directions by optical lithography and reactive ion etching. The dimensions of the mask openings and mask periods ranged from 4 to 8 μm and from 6 to 300μm, respectively. The growth parameters of the second epitaxial process have been optimized to grow triangularly shaped GaN:Si stripes in the mask openings for both stripe orientations. This leads to (11-22)-facets for the <1-100>-oriented stripes and (1-101) facets for the <11-20>-oriented stripes, respectively. On these n-doped GaN stripes we have grown GaInN quantum wells containing about 10% In followed by a p-doped GaN top layer. This enabled us to examine the influence of the different crystal orientations on the spectral properties of the quantum wells by photoluminescence and cathodoluminescence, hence giving information about the internal piezoelectrical field and indium composition homogeneity. Moreover, these samples have been electrically contacted by simple In test contacts. 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. [1] T. Takeuchi et al., Jpn. J. Appl. Phys. 39 (2000) 413.

E11.33

Growth of Bulk GaN by Ga Vapor Transport. Phanikumar Konkapaka[1], Huaqiang Wu[1], Yuri Makarov[2] and Michael G. Spencer[1]; [1]Electrical and Computer Engineering, Cornell University, Ithaca, New York; [2]Semiconductor Technology Research, Inc., Richmond, Virginia.

Gallium Nitride is a direct wide band gap semiconductor that is used for a wide variety of applications such as light emitting diodes [LED], lasers [LD] and high electron mobility transistors [HEMT]. However, most of the state of the art GaN devices are fabricated on foreign substrates such as Sapphire or Silicon Carbide because of the absence of commercially available Gallium Nitride substrates. Homoepitaxy on GaN substrates decreases the dislocation densities in the epitaxial layers and help increase the performance of the GaN devices. Hence, growth of bulk GaN single crystals is necessary to provide the needed momentum to advance the device development. In the present discussion, bulk GaN single crystals were grown using Ga vapor transport. GaN powder and Ammonia are used as the precursors for growing bulk GaN. Nitrogen is used as the carrier gas to transport the Ga vapor that is obtained from the decomposition of GaN powder. Growth of bulk GaN is performed in a resistively heated reactor that is dedicated for bulk GaN growth. During the process, the source GaN powder was kept at 1155 degrees C and the seed at 1180 degrees C. Using this process, it was possible to achieve growth rates of above 200 microns/hr. The GaN layers thus obtained were characterized extensively using X-Ray diffraction [XRD], scanning electron microscopy [SEM], atomic force microscopy and X-Ray topography. X-ray diffraction patterns showed that the grown GaN layers are single crystals oriented along c direction. High-resolution X-ray diffraction showed triple crystal rocking curves (TCRC) as narrow as 36 arcsec. TEM images of the cross section have shown dislocation densities as low as 1x106/cm2. AFM studies indicated that the dominant growth mode is dislocation mediated spiral growth. From the SEM images, V-defects were observed on the grown layers. Electrical and Optical characterization were also performed on these samples. Hall mobility measurements indicated a mobility of 550 cm2/V.s and a carrier concentration of 6.67 x 1018/cm3. The characterization results on the growth samples and the consequent progress of this growth technique will be presented in detail.

E11.34

Self Oriented Growth of GaN Films on Molten Gallium. Mahendra K. Sunkara[1], Hongwei Li[1], Hari Chandrasekaran[1], Michael Stukowski[2] and Krishna Rajan[2]; [1]Chemical Engineering, Univ. of Louisville, Louisville, Kentucky; [2]Materials Science & Engineering, Rensselaer Polytechnic Institute, Troy, New York.

The need for native GaN substrates is quite high as the use of lattice-mismatched substrates causes high density of misfit dislocations in the epitaxial GaN layers. In this regard, there have been tremendous efforts to synthesize large area bulk III-nitride crystals with low defect densities. To date, bulk growth processes using high pressures and temperatures produced 15 mm sized crystals only. Solution growth from gallium melt under super high pressure as well as physical vapor transport technique only produced millimeter sized GaN single crystals which cannot be used as substrates to fabricate devices with a reasonable cost. We have recently demonstrated a concept in which hexagonal GaN crystals could orient on top of molten gallium to form large area single crystal quality films. In this presentation, a systematic and thorough study is performed to understand the self-orientation within the resulting films. The direct nitridation experiments were performed by exposing 2 to 500 microns Ga films on amorphous quartz substrates to atomic nitrogen in an ECR-MW plasma reactor. Several experiments using stationary stage showed the self-oriented regions could be as large as 5 mm or higher. The grain size estimated from top view of GaN film is about 4-5 microns with a thickness of 19 microns for nitridation time scales of 5h. Micro-Raman spectra showing a peak at 144 cm-1 confirmed the wurtzite phase of GaN. XRD Θ-2Θ scans showed predominant reflections of (0002) and (0004) planes indicating C-plane orientation. The cross-sectional SEM indicates the presence of molten gallium layer below the self-oriented regions. Cross-section TEM of the self-oriented GaN shows no contrast from dislocations inside the

grains but indicates the presence of stacking faults. The boundaries between the neighboring crystals were analyzed using convergent beam electron diffraction (CBED) technique for misorientaion and dark field images under two-beam condition for defects.

E11.35

Electrical and Optical Properties of 1 MeV-electron irradiated $Al_xGa_{1-x}N$. Michael R. Hogsed[1], Mo Ahoujja[2], Mee-Yi Ryu[3,1], Yung Kee Yeo[1], James C. Petrosky[1] and Robert L. Hengehold[1]; [1]Department of Engineering Physics, Air Force Institute of Technology, Wright-Patterson AFB, Ohio; [2]Department of Physics, University of Dayton, Dayton, Ohio; [3]University of Dayton Research Institute, Dayton, Ohio.

Group III-nitrides have long been regarded as being more tolerant to high energy particle radiation than is GaAs and other commonly used semiconductors, though relatively few studies have been done to quantify this expected advantage. The effect of radiation upon GaN material properties such as carrier concentration, mobility, and luminescence efficiency were reported in recent years. Additionally, a few radiation-induced point defects for GaN were characterized, providing some insight into the mechanism underlying radiation-induced changes. However, radiation effects upon the important ternary alloy, AlGaN, are not well studied, though these effects are sure to have bearing on the radiation response of AlGaN/GaN HEMTs and other devices. Here, the electrical and optical properties of 1.0 MeV-electron irradiated n-$Al_xGa_{1-x}N$ are studied for aluminum mole fraction from x = 0 to 0.30 using deep level transient spectroscopy (DLTS), variable temperature Hall, and cathodoluminescence (CL) measurements. DLTS measurements revealed electron traps in GaN that are characteristic of those designated E, D, C, B, and A traps in the literature. We have found corresponding energy levels from the $Al_xGa_{1-x}N$ samples, and they are shown to become deeper as the aluminum mole fraction increases. Carrier concentration of $Al_xGa_{1-x}N$ samples before and after electron irradiation were measured as a function of dose. The carrier removal rate is shown to be strongly dependent on initial carrier concentration, confirming the role of shallow donor complexing in irradiated n-$Al_xGa_{1-x}N$. For example, the carrier removal rate of $Al_{0.2}Ga_{0.8}N$ is 0.40 and 4.2 cm^{-1} in samples having respective carrier concentrations of $8x10^{16}$ and $6x10^{17}$ cm^{-3}. The carrier removal rate is found to depend only slightly on aluminum mole fraction. CL peak intensity was reduced significantly following irradiation, indicating the introduction of non-radiative recombination centers during irradiation. Upon irradiation with a dose of $6x10^{16}$ cm^{-2}, the CL peak intensity was reduced 40 to 60% in the various $Al_xGa_{1-x}N$ samples. For comparison, we also irradiated and characterized an n-GaAs sample under identical conditions and found that the carrier removal rate was 8.7 cm^{-1} and CL peak intensity was reduced by more than 99%.

E11.36

Comparative Study of GaN Based Light Emitting Devices Grown on Sapphire and GaN Substrates. Stephan Figge[1], Sven Einfeldt[1], Claudia Roder[1], Detlef Hommel[1], Tanya Paskova[2] and Bo Monemar[2]; [1]Institute of Solid State Physics, University of Bremen, Bremen, Bremen, Germany; [2]Department of Physics and Measurement Technology, Materials Science, Linkoeping University, Linkoeping, Sweden.

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 (LEDs) grown simultaneously by metal organic vapor phase deposition (MOVPE) on both free standing HVPE GaN substrates and directly on sapphire. Despite the lower defect density of the GaN substrates one drawback is their limited size and a pronounced domain structure. High resolution x-ray diffraction reveals a multi peak structure with several distinguishable peaks in 002 omega scans when using a hybride monochromator with an elongated spot of 12 mm^2 in size. This indicates a domain size of these substrates in the order of a square millimeter. The temperature dependence of the lattice constants indicates that the GaN layer on the MOVPE templates 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. An advantage of the GaN substrates is their five times higher thermal conductivity compared to sapphire. Therefore, the devices grown on HVPE GaN substrates operate up to higher currents due to a lower thermal resistivity of the device. The electro-optical data will be related to theoretical calculations on the thermal resistivity of the devices. The data show a good agreement between the calculated thermal resistivities and the decrease of the output intensity at higher operation currents. The LEDs grown on GaN substrates exhibit no decrease of ouput intensity up to operating currents above 500 mA. 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.

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. Jie Bai[1], Michael Dudley[1], Balaji Raghothamachar[1], Li Chen[2], Brian Skromme[2], Philip Hartlieb[3], Emily Michaels[3], Joseph William Kolis[3], Brian Wagner[4], Robert Davis[4], Uttiya Chowdhury[5] and Russell Dupuis[5]; [1]Materials Science & Engineering, Stony Brook University, Stony Brook, New York; [2]Department of Electrical Engineering and Center for Solid State Electronics Research, Arizona State University, Tempe, Arizona; [3]Department of Chemistry, Clemson University, Clemson, South Carolina; [4]Department of Materials Science and Engineering, North Carolina State University, Raleigh, North Carolina; [5]School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, Georgia.

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 3.2eV 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 existence and strength of the 3.4 eV peak are found to be related to the I2 type BSF (RI2=1/3<10-10>) observed in these samples. To relate the 3.2 eV peak with structural defects, a series of GaN epilayers grown on either SiC (of various off cut angles) or sapphire is investigated by TEM and PL spectroscopy. The occurrence of this PL peak is shown to be correlated to the observation of prismatic stacking faults (PSF, Rp=1/2<10-11>), which are folded from I1 type BSFs (RI1=1/6<20-23>). The 3.2 eV peak (attributed to PSF) is always accompanied by the 3.4 eV peak (attributed to the cubic phase formed by I1 type BSF, in this case), which confirms that the 3.4 eV peak is related to the presence of the cubic phase in the crystal. Conventional and high resolution TEM characterization of the above-mentioned stacking faults and the mechanism by which they form on both sapphire and SiC substrates will be presented.

E11.38

Growth of GaN from Elemental Gallium and Ammonia via Modified Sandwich Growth Technique. Elif Berkman[1], Ramon Collazo[1], Raoul Schlesser[1], Zlatko Sitar[1], Dang Cai[2] and Hui Zhang[2]; [1]Department of Materials Science and Engineering, North Carolina State University, Raleigh, North Carolina; [2]Department of Mechanical Engineering, Stony Brook University, Stony Brook, New York.

As an alternative to the MOCVD process, gallium nitride (GaN) thin films were grown on (0001) sapphire substrates at 1050°C by controlled evaporation of gallium (Ga) metal and reaction with ammonia (NH_3) at a total reactor pressure of 800 Torr. Pure nitrogen (N_2) was flowed directly above the molten Ga source. This flow prevented direct reaction between the molten Ga source and ammonia, which causes Ga spattering and GaN crust formation, substantially enhanced Ga evaporation rate and, at the same time, enabled control of Ga transport to the substrate. Continuum modeling provided information on flow dynamics. A simple mass transport model based on total reactor pressure, gas flow rates and source temperature was developed and verified. Velocity streamlines and mass fraction distributions of ammonia inside the reactor as well as growth rate measurements for different ammonia flow rates and source-to-substrate distances showed that the maximum growth rate was controlled by transport of both Ga species and reactive ammonia to the substrate surface. A growth rate of 1.4 μm/h was obtained at 1050°C, 800 Torr, 3 slm of ammonia, and 1250°C Ga source temperature with a 24 mm source-to-substrate distance. XRD measurements revealed a full-width at half-maximum (FWHM) of 0.6 deg. for the (0002) GaN peak. Experimental variables and improvements in the overall growth process regarding the transport of species and the quality of the grown crystals will be presented.

E11.39

Resonant Photoemission Shake-up Process at the 3p Photothreshold in GaN. Lukasz Plucinski[1], T. Learmonth[1], Kevin E. Smith[1], Alex Zakharov[2], I. Grzegory[3], T. Suski[3], S. Porowski[3], B. J. Kowalski[4], I. Friel[5] and Theodore D. Moustakas[5]; [1]Physics, Boston University, Boston, Massachusetts; [2]Max-Laboratory, Lund University, Lund, Sweden; [3]High Pressure Research Centre, Polish Academy of Sciences, Warsaw, Poland; [4]Institute of Physics, Polish Academy of Sciences, Warsaw, Poland; [5]Electrical and Computer

Engineering Department, Boston University, Boston, Massachusetts.

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 $3d^8$ multiplet. Satellite lines exhibit the resonance for $h\nu$ = 104 - 112 eV. The measurements were performed at the 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 photoemission measurements on these samples since they are very thin platelettes and cleaved surfaces have areas in order of 0.1 × 2 mm^2 or less. The constant initial state (CIS) spectra were 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 $3d^8$ holes resulting from the super Coster-Kronig decay of the 3p core hole [6]. The nature of the process is quasiatomic, however, final state screening is material specific. We have performed detailed measurements in the photon energy range $h\nu$ = 90 - 120 eV. The 3.6 eV separation of the two main peaks related to the ^{1}G and ^{1}F terms of the $3d^8$ multiplet at binding energies 53.6 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 ^{1}D term, whereas the feature at 55.5 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-0311792 and INT-01-04605, and the U.S. Army Research Office under grant 40126-PH. [1] T.-C. Chiang and D. E. Eastman, Phys. Rev. B 27, 5749 (1980). [2] S. Suzuki, T. Kiyokura, F. Maeda, K. G. Nath, Y.Watanabe, T. Saitoh, and A. Kakizaki, J. Elec. Spectroscopy 114-116, 421 (2001). [3] U. Johansson, R. Nyholm, C. Törnevik, and A. Flodström, Rev. Sci. Instrum. 66, 1398, (1995). [4] I Grzegory, J. Phys.: Condens. Matter 14, 11055 (2002). [5] D. Doppalapudi, E. Iliopoulos, S. N. Basu, and T. D. Moustakas, J. Appl. Phys. 85, 3582 (1999). [6] L. C. Davis and L. A. Feldkamp, 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.

A. Yu. Nikiforov[1], G. S. Cargill III[1], V. Dierolf[2], C. J. Collins[3], A. V. Sampath[3], G. A. Garrett[3], H. Shen[3] and M. Wraback[3]; [1]Materials Science and Engineering, Lehigh University, Bethlehem, Pennsylvania; [2]Physics, Lehigh University, Bethlehem, Pennsylvania; [3]Sensors and Electron Devices Directorate, U. S. Army Research Laboratory, Adelphi, Maryland.

Measurement of luminescence spatial nonuniformity has proven to be an important technique for the study of carrier localization associated with compositional fluctuations in nitride alloys such as $In_xGa_{1-x}N$. In this paper, homogeneity of luminescence and composition in $Al_xGa_{1-x}N$ films with x 0.2 - 0.6 grown by plasma-assisted MBE on hydride vapor phase epitaxy (HVPE) GaN templates and sapphire substrates have been investigated by spatially resolved ultraviolet confocal photoluminescence microscopy and cathodoluminescence (CL) spectroscopy, with mapping at temperatures in the range 10K-300K. In all cases, AlN buffer layers were employed to prevent cracking in the AlGaN epitaxial layers. The films studied have nonuniformities on scales of 50nm to 10 m observed as bright dots in CL intensity maps and variations in the CL spectra. The single band room temperature CL spectra from bright areas are shifted to longer wavelengths and are broader than the CL spectra from dark areas. At low temperature, two peaks can be distinguished in CL spectra. The CL intensity maps corresponding to these peaks show pronounced differences. These data, in conjunction with the observation that as the temperature is lowered the difference in intensity between bright and dark regions is strongly reduced, suggest the presence of thermally activated transport into regions of the sample characterized by the longer wavelength emission. Surface morphology observed by secondary electron microscopy is correlated, as a function of growth conditions, with the luminescence intensity and the scale and density of luminescence fluctuations. Optimized films with very strong luminescence intensity at wavelengths in the 280nm to 320nm spectral range for potential applications in UV LED active regions have been produced.

E11.41

Scanning Electron Microscopy Cathodoluminescence Studies of Piezoelectric Fields in an InGaN Multiple Quantum Well Light Emitting Diode. Kristin L. Bunker[1,2], Roberto Garcia[1] and Phillip E. Russell[1,2]; [1]Materials Science and Engineering, North Carolina State University, Raleigh, North Carolina; [2]Analytical Instrumentation Facility, North Carolina State University, Raleigh, North Carolina.

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). The existence and direction of the piezoelectric field in the InGaN-based device were investigated using SEM-CL peak voltage dependence 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 polychromatic spectroscopy setup consisted of a USB2000 Ocean Optics miniature spectrometer coupled via a fiber optic light collection system. The spectrometer is a 2048-element linear CCD array and was configured with a 50 m slit, a 600 lines/mm grating, a spectral window between 350nm-1000nm, and 2nm optical resolution. A 1000 micron fused silica fiber optic terminated with a SMA 905 connector was connected to the spectrometer via a vacuum feedthrough. A 5.1 mm2 Si photodetector on a TO-5 header mount was used to collect panchromatic CL images. The custom sample holder was designed to allow simultaneous placement and positioning of the fiber optic and Si photodetector as well as provide electrical contact to the sample. The CL emission peak showed a blueshift with increasing reverse bias due to the cancellation of the piezoelectric field. A full compensation of the piezoelectric field was observed followed by a redshift with a further increase of reverse bias, indicating that flat band conditions had been reached. We determined the piezoelectric fields point in the [000-1] direction and estimated the magnitude to be approximately 1.0±0.2 MV/cm by calculating the depletion region thickness from the donor and acceptor concentrations, the built-in potential, and the applied voltage. A blueshift of the CL emission peak was also observed as the carrier generation density increased or the beam current increased (and hence the total carrier injection level). In the EL experiment, a 10 nm blueshift was observed as the forward bias was increased from 2.1 volts to 5.0 volts. The blueshift phenomenon observed in the SEM-CL carrier generation and EL experiments is due to the screening or weakening of the piezoelectric field by the injected or beam generated carriers in the quantum well.

E11.42

Abstract Withdrawn

E11.43

Non-Polar GaN/AlN Superlattices on A-plane AlN (500nm) Buffer Layers Grown by RF-MBE. Takayuki Morita, Akihiko Kikuchi and Katsumi Kishino; Electrical and Electronics Engineering, Sophia University, Tokyo, Japan.

The fabrication of GaN/AlN intersubband transition (ISBT) crystals, in which the piezo-electric field does not be applied, is very interesting for the application to 1.55μm ultra-fast optical communication devices with complicated multi-layered quantum heterostructures. The piezo-electric field sometime 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/AlN quantum heterostructures were grown on R-plane (10-12) sapphire substrates. For suppressing the crystal crack, GaN/AlN supperlattices should be prepared on thick AlN buffer layers, but the growth technology of A-plane AlN on R-plane sapphire was not always established so far. So first, changing the growth condition, A-plane AlN were grown, where important factors were the V/III ratio and the growth temperature. Compared with the growth on C-plane sapphires, growing under the III-rich condition at higher temperatures was essential for obtaining high crystal quality. Note that the growth temperature on C-plane is 800 ^{0}C. The growth temperature was changed in the range from 830 to 900 ^{0}C, and in the whole area A-plane AlN was obtained. A highest quality AlN was prepared at 850 ^{0}C with the growth rate of 500nm/hr. The one-hour growth produced the 500 nm AlN and the surface roughness was evaluated by AFM with the RMS value of 4 nm. Nonpolar 50 pairs of GaN/AlN superlattices were grown on 500 nm A-plane AlN buffer layers. The X-ray diffraction peaks from the R-plane sapphire substrate and the A-plane GaN/AlN superlattice and the satellite peak were clearly resolved. From the XRD satellite peak, the thickness of GaN well was 11 mono-layer (ML) and AlN barrier 12 ML. The low temperature photoluminescence spectroscopy was performed observing the PL peak at 334nm, which was well coincident with the calculated value of (340nm) based on the flat band model. A similar size GaN/AlN superlattices were grown on C-plane sapphire substrate, but in this case the PL peak was at 360nm, showing red-shift. This result clearly shows that the piezo-electric field does not be functioned in A-plane GaN/AlN superlattices grown on R-plane sapphire substrates This work was

supported by a Grant-in-Aid for Scientific Research (A) #14205057 from the Ministry of Education, Culture, Sports and Technology and a NEDO Industrial Technology Research Grant #02A23041d

E11.44

Combinatorial Study of Nickel-Gold P-Contacts for Blue InGaN Light Emitting Diodes (LEDs). Michael T. Ahrens[1,4,2], Edward B. Stokes[1,2], Albert Davydov[3], Abhishek Motayed[5], Theodore Robert Harris[1,3] and S. Tiffany Morton[1]; [1]Electrical and Computer Engineering, University of North Carolina at Charlotte, Charlotte, North Carolina; [2]Center for Optoelectronics and Optical Communications, University of North Carolina at Charlotte, Charlotte, North Carolina; [3]Metallurgy Division, National Institute of Standards and Technology (NIST), Gaithersburg, Maryland; [4]Dot Metrics Technologies, Charlotte, North Carolina; [5]Howard University, Washington, District of Columbia.

In this paper, a combinatorial study on nickel-gold transparent p-type contacts for blue InGaN light-emitting diodes (LEDs) will be presented. A spatial array of various nickel-gold p-contacts is applied to a single LED wafer using the e-beam deposition technique, and annealed using rapid thermal annealing (RTA), with variations imposed on nickel-gold thickness and RTA conditions. The effects on contact transparency and LED efficiency of the Ni-Au thickness ratio, the temperature of the RTA anneal, and the RTA environment will be presented.

E11.45

Optical Properties of II-IV-N_2 Semiconductors. John F. Muth[1], Andrei Osinsky[4], Henry Everitt[2] and Ivan Avrutsky[3]; [1]ECE Dept Box 7911, NC State University, Raleigh, North Carolina; [2]Physics, Duke University, Durham, North Carolina; [3]ECE Dept, Wayne State University, Detroit, Michigan; [4]SVT Associates, Eden Prairie, Minnesota.

Recently, wide band gap II-IV-N_2 semiconductors such as $ZnSiN_2$, and $ZnGeN_2$ and $ZnSiGeN_2$ have been synthesized, but very little is known about their band structure, optical properties, or electronic properties. Bulk crystals are hard to synthesize because high temperatures and pressures are required. The success in growing II-IV-N films epitaxially by MOVCD creates interesting opportunities.[1] The crystal structure of II-IV-N_2 compounds is orthorhombic, and when grown on r-plane sapphire can provide a suitable template for GaN growth. Optical transmission studies of the band edge of $ZnSiN_2$ and $ZnSiGeN_2$ with varying Si and Ge percentages were conducted. The indirect nature of the band gap was confirmed, and prism coupling was used to obtain the refractive indices in the visible and NIR portion of the spectrum. Although the crystal symmetry was orthorhombic, the refractive indices indicated uniaxial optical properties. Optical loss measurements indicate that the films are suitable for waveguides and novel devices based on birefringent optical effects. [1] A. Osinsky, V. Fuflyigin, L. D. Zhu, A. B. Goulakov, J. W. Graff, and E. F.Schubert, Proceedings of the 2000 IEEE/Cornell Conference on High Performance Devices, 2000, p. 168.

SESSION E12: Nanostructures
Chairs: Mike Manfra and Christian Wetzel
Friday Morning, December 3, 2004
Back Bay C (Sheraton)

8:30 AM *E12.1

One-Dimension Group-III Nitride Nanostructures: Growth, Structure, and Their Luminescence and Electrical Properties. Li-Chyong Chen[1] and Kuei-Hsien Chen[2]; [1]Center for Condensed Matter Sciences, National Taiwan University, Taipei, Taiwan; [2]Institute of Atomic and Molecular Sciences, Academia Sinica, Taipei, Taiwan.

I will present our work on the one-dimensional (1D) III-N nanostructures such as nanowires, nanorods, nanobelts, nanocables and nanotips. 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 and their resultant 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@GaN nanocables have a PL FWHM of only 7 meV. 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 and nanotips-array field emission diode and their implications will also be discussed.

9:00 AM E12.2

MOCVD growth and characterization of GaN nanowires. Gela Kipshidze[1], Boris Yavich[1], Jongsin Yun[1], Anilkumar Chandolu[1], Vladimir Kuryatkov[1], Deeder Aurongzeb[2], Mark Holtz[2] and Henryk Temkin[1]; [1]Electrical Engineering, Texas Tech University, Lubbock, Texas; [2]Department of Physics, Texas Tech University, Lubbock, Texas.

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 TMG 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 sidewalls. 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 300nm. With the growth rate of the order of 1 μm/hr the length of nanowires can be readily controlled up to 2μm. Structural and optical properties of GaN nanowires were studied by scanning electron microscopy (SEM), x-ray diffraction, and cathodoluminescence (CL). Symmetric 2Θ-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 bandedge peak at 3.336eV (368nm), 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; [2]Chemistry & Biochemistry, University of California, Santa Barbara,, California; [3]Materials, 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 2.6K. 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 voltage-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 measurememt 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 MOCVD. Jie Su[1], Maria Gherasimova[1], George Cui[1], Jung Han[1], Steve Lim[2], Dragos Ciuparu[2], Lisa Pfefferle[2], Yiping He[3], Arto Nurmikko[2], Christine Broadbridge[4] and Ann Lehman[5]; [1]Department of Electrical Engineering, Yale University, New Haven, Connecticut; [2]Department of Chemical Engineering, Yale University, New Haven, Connecticut; [3]Division of Engineering, Brown University, Providence, Rhode Island; [4]Department of Physics, Southern Connecticut State

University, Hamden, Connecticut; [5]Trinity College, Hartford, Connecticut.

Nanowires from wide bandgap GaN are of contemporary interest for applications in nano- electronics and photonics. So far GaN nanowires are synthesized primarily by hot-wall, furnace-based flow reaction with near-equilibrium process condition. The synthesis of nanowire heterostructures by modern hetero-epitaxial technologies such as MBE and MOCVD would have advantages including a better-controlled process environment that will facilitate microscopic understanding of synthesis mechanisms, and the possibility of tailoring the chemical composition on the atomic scale, thus enabling the realization of novel quantum structures and metastable configurations. Here we report the first growth of III-nitride nanowires and heterostructures using vapor-liquid-solid (VLS) growth mode in a conventional horizontal MOCVD reactor. It was observed that both supersaturation and growth stoichiometry (V/III ratio) play crucial roles in maintaining the presence of liquid droplets; a slight deviation leads to either the formation of tapered crystallites or micron-size droplets. Indium was introduced as an in-situ catalyst based on thermodynamic consideration to sustain the liquid droplets and alleviate their sensitive dependence on stoichiometry. Silica-based mesoporous templates (MCM-41) were employed to control the coalescence of liquid catalyst and to facilitate heterogeneous nucleation. SEM and TEM reveal that GaN nanowires, with 20-60 nm in diameters and up to 10 um in length, exhibit a triangular cross section with growth direction along <10-10>. AlGaN/GaN heterostructures were prepared by modulating the TMGa and TMAl flows. At relatively low Al concentrations (<30%), one dimensional nanowires with varying Al compositions along the longitudinal direction were examined using selective-area high resolution EDS. As the Al concentration approaches the binary end (AlN), three-dimensional nano-scale Christmas tree (trunk:GaN/branch:AlN) heterostructures were observed. The AlN branches are co-planar with the GaN trunk (on basal plane) and are pointed along four of the six equivalent {10-10} directions, having an angle of 60 deg to the trunk. The understanding of kinetics and thermodynamics in the MOCVD synthesis of GaN nanowires has also enabled us to prepare aligned, epitaxial nanostructures on single crystal substrates. The authors acknowledge the support of DOE NETL and NSF.

9:45 AM E12.5
Gallium Nitride-Based Nanowire Radial Heterostructures for Nanophotonics. Yat Li, Fang Qian, Silvija Gradecak, Deli Wang, Carl J. Barrelet and Charles M. Lieber; Department of Chemistry and Chemical Biology, Harvard University, Cambridge, Massachusetts.

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 nanowire materials studied to date, the group III-nitrides represent an especially attractive system for exploration since heterostructures offer the opportunity to prepare efficient nanoscale injection structures that produce light over a large range of frequencies. To this end we report the first successful synthesis of well-defined GaN/InGaN/GaN core-shell-shell (CSS) nanowire heterostructures. These new CSS nanowires were grown by metalorganic chemical vapor deposition in which the core nanowire was defined by a nanocluster-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 InGaN 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.

10:30 AM E12.6
Catalytic Growth of GaN Nanowires by Hydride Vapor Phase Epitaxy. George Seryogin, Ilan Shalish, Warren Moberly Chan and Venkatesh Narayanamurti; Division of Engineering and Applied Sciences, Harvard University, Cambridge, Massachusetts.

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 nano-scale wire structure. To date, GaN nanowires have been grown by virtually all the known methods for growing GaN. Among the nanowire growth modes, catalytic growth (vapor-liquid-solid) is commonly favored for the certain degree of control it offers over wire size and position. Hydride vapor phase epitaxy (HVPE) of GaN nanorods was reported by Kim et al [APL 81, 2193 (2002)]. However, no catalytic growth has been reported using HVPE. In film growth, HVPE presents several advantages over the more common metal-organic vapor growth methods, such as high growth rates of over 100 μm/hour and carbon free/self cleaning, resulting in high quality GaN with record high mobility. For nanowire growth, HVPE presents very specific challenges. The fast growth rate presents a strong competition between direct vapor growth (usually undesired as it tends to thicken the wires) and the desired vapor-liquid-solid catalytic growth mode. Furthermore, the HCl produced in the reaction of GaCl and ammonia tends to etch away the metal catalyst. Hence, the only report to date on HVPE growth of GaN nanostructures was not catalytic (no ability to define or pattern the growth site) and was of limited aspect ratio. We report on a first successful attempt at catalytic growth of large aspect ratio GaN nanowires. The growth was carried out in a custom-built HVPE 75 mm-diameter quartz tube reactor on Si(111), sapphire, and ZnO substrates, using Au, Ni, Co, and Fe as catalysts. GaCl was formed by a direct reaction of high-purity Ga with HCl at 850 ^{o}C. Nitrogen was used as the carrier gas at a rate of 3000 sccm at atmospheric pressure. HCl and ammonia flows were in the ranges of 1 to 15 sccm and 50 to 200 sccm respectively. Scanning and transmission electron microscopies, energy dispersive spectroscopy, and room temperature photoluminescence were used to characterize the nanowires. The obtained GaN nanowires were 20 to 400 nm-thick with typical lengths of several microns. Relative to other methods, HVPE growth of nanowires is fast (up to ten microns per minute), and takes place at relatively low temperatures (630 to 780 ^{o}C). The catalytic growth mode enables control over the site of growth resulting in dense arrays, well defined on the micrometer scale, that on sapphire and ZnO substrates align well along the GaN c-axis. Transmission electron microscopy reveals a monocrystalline structure. The band-edge photoluminescence peaks at 3.25 eV, red-shifted compared with values commonly observed in GaN films (3.42 eV). In summary, we demonstrate GaN nanowires can be grown by the vapor-liquid-solid mechanism using metal catalysts in a hydride vapor phase epitaxy process.

10:45 AM E12.7
Nucleation Studies of AlN/GaN Nanostructures. Shalini Gupta[1], Martin Strassburg[1,2], Ali Asghar[1], Hun Kang[1], Adam M. Payne[1], Ian T. Ferguson[1], Jayantha Senawiratne[2] and Nikolaus Dietz[2]; [1]ECE, Georgia Institute of Technology, Atlanta, Georgia; [2]Physics, Georgia State University, Atlanta, Georgia.

The efficiency of optical luminescence in semiconductors is strongly limited as bandgap increases. For example, the luminescence intensity in AlGaN epilayers decreases with increasing Al concentration. Nanostructures have been proven to enhance the performance and efficiency of optoelectronic devices. Thus, the potential of the GaN/AlN heterostructures for the fabrication of quantum structures needs 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 Stranski-Krastanow-like 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 AlN on GaN, Metal-Organic Chemical Vapor Deposition (MOCVD) may offer a growth window to establish AlN quantum structures on GaN surface. Nucleation studies of the AlN on strained GaN epitaxial films are presented. A novel two step growth process is proposed for the control of nucleation and growth of nano-structures 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 applied to adjust the nanostructure distribution. The surface morphology, size, and density of the nanostructures were analyzed using Atomic Force Microscopy (AFM). According to the respective growth conditions, the lateral size and height of 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 x 10^{8}cm^{-2}to 1 x 10^{11}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 AlN A1 (TO) and A1 (acoustic overtone) modes were observed. However, the energy position of the Raman modes is shifted from the value of bulk AlN. Uniaxial strain and/or alloying with the buried GaN are suggested to cause the observed deviation. The UV optical properties of these devices will also be discussed.

11:00 AM E12.8
Effect of the Polar Surface on GaN Nanostructure Morphology and Growth Orientation. Chang-Yong Nam, Douglas Tham and John E. Fischer; Materials Science and Engineering, University of Pennsylvania, Philadelphia, Pennsylvania.

Along with recent extensive research interest in nanotechnology, gallium nitride (GaN) one-dimensional nanostructures, such as nanowire and nanobelt (or nanoribbon), are actively studied for possible future device applications. Generally, nanostructure synthesis

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 2010F) 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
Determination of Nanowire Growth Direction by Electron Diffraction. Douglas Tham, Materials Science and Engineering, University of Pennsylvania, Philadelphia, Pennsylvania.

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