SYMPOSIUM Y
Y: GaN and Related Alloys
December 1 - 5, 2003

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*Invited paper
8:30 AM Y1.1
Ultraviolet Laser Diodes With AlGaN and InAlGaN Multiple Quantum Wells (MQW) Laser diodes emitting in the ultraviolet spectral region. The nitride laser diodes were grown on 0001 substrate by metal organic chemical vapor deposition. Under pulsed bias conditions, laser operation was obtained in a gain-guided laser device with an increased mirror facets and cavity lengths ranging from 300 to 1500 µm. For low-power diodes with AlGaN MQW active regions, room-temperature threshold current densities as low as 23 kA/cm² have been achieved with emission wavelengths between 361.6 nm and 358.5 nm. This is the shortest emission wavelength yet reported for a semiconductor laser diode. The maximum output power for AlGaN MQW laser diodes was 45 mW per facet with differential quantum efficiencies of 1.13%. Slightly improved performance has been obtained for laser diodes with InAlGaN MQW active regions. The indium composition in the quantum wells ranged from 0.5% to 3% and the aluminum content varied between 2% and 4%. Pulsed laser operation has been obtained with threshold current densities by increasing the current density by a factor of two. Low-loss diodes with much lower loss than the above-mentioned laser diodes may be achieved for LEDs and high-speed photodetectors.

*The work was partially supported by the Defense Advanced Research Projects Agency (DARPA) program under the Photonics Systems Incubator (PSI) contract N00014-02-C-0017.


9:00 AM Y1.2
298 nm Ultraviolet (UV) Light Emitting Diodes on Sapphire and Bulk AlN Substrates. Yong-Ho Bae, Qi-Yun Zhao, B. I. Seo, H. G. Kwon, J. C. Song, and W. W. Chow. 2. Dr. H. G. Kwon.

We report on epitaxial growth, fabrication, and characterization of 298 nm ultraviolet (UV) LEDs on sapphire and bulk AlN substrates. Single crystal bulk AlN substrates of approximately 4x5 mm size and 1 mm thick were supplied by Crystal IS, Inc. The LED structures were grown on the AlN substrate by metalorganic chemical vapor deposition. The resulting LEDs were not operated under pulsed bias conditions and the LED emission was 4x3 mm size.

9:15 AM Y1.3
High Current Injection to a UV-LED grown on a Bulk AlN Substrate. Toshiaki Nishida1, Tomoyuki Hon2, Hiroshi Saito1 and Toshiaki Masamoto3.

We fabricated an AlGaN-based ultraviolet light emitting diode (UV-LED) on a bulk AlN substrate. The device shows improved saturation characteristics in its output under high current injection. The device was then operated under pulsed bias conditions. Thermal conductivity and transparency of the substrate material are important for high flux extraction from LEDs. Heat dissipation improves the radiative carrier recombination and reduction of the UV light absorption enhances the extraction efficiency. Bulk AlN is UV transparent and has high thermal conductivity of 285 W/cmK, which is the highest among the conventional nitride substrates. The device was then operated under pulsed bias conditions. The device consists of an AlGaN single quantum well (AlGaN/SiO₂) sandwiched between the high-resistance p-type and n-type carrier block layers [1] and short-period-alloy superlattice (SPASL) cladding layers [2]. The emission wavelength was 345 nm. For comparison, we fabricated a reference device on a high-quality AlN template layer grown on a sapphire substrate [3]. The p-type electrode areas are 300x300 micrometers square, and output powers are measured under base-current geometry on a metal block. The output power of the UV-LED on the bulk AlN substrate increased almost linearly up to 300 mA and saturated at the injection current of 400 mA, which is two times higher than that of the reference device.

The AlGaN material system enjoys high scientific and technological interest because of its prospects for development of deep UV light-emitting diodes (LEDs). We report on the material growth conditions, device fabrication and measurement of deep UV light-emitting diodes using AlGaN/AlGaN heterostructures grown using Metalorganic Chemical Vapor Deposition (MOCVD). The epitaxial layers were grown on both polished sapphire substrate for development of backside illuminating LEDs. A multiple low temperature buffer layer scheme was used to grow thick AlGaN template layers without cracking. Reduction of threading dislocation density using this scheme was studied using transmission electron microscopy. The layers were grown in a low pressure (LP) MOCVD reactor using a growth pressure from 50 to 200 Torr and growth temperature from 1050 to 1070°C. For mesa etching, the resistance of the bottom n-contact layer plays a decisive role in the forward resistance of the device. The device has a design for low temperature buffer layers. The device also has to be transparent to the device luminescence (λ ~ 380 to 310 nm). The contact layer is made up of a 0.5 µm thick n-contact layer for this purpose having a sheet resistivity of ~ 1000 Ω/square as measured by contactless resistivity probe.

investigate the effects of a current-blocking layer to eliminate or reduce luminescence from the GaN core layer.

10:30 AM 4Y1.6 Light Emission Devices Using Polaron and Non Polaron III-N Films, M. Asif Khan, Department of Electrical Engineering, University of South Carolina, Columbia, South Carolina.

In this paper we will discuss the progress that we have made in fabricating high efficiency deep ultraviolet light emission devices (LEDs) and superlattices. Results will be presented of a comparative study of devices with ternary AlGaN and quaternary AlGaN/GaN multiple quantum well (MQW) active regions. With improved buffer layers and active region designs we can now achieve milliwatt levels of power even at wavelengths from 267 nm to 340 nm. These devices are well suited as pumps for phosphors for visible and white light generation. Recently, for the first time we have also succeeded in fabricating V-NV-LEDs using non-polar GaN N-polytype AlGaN/GaN MQW's over GaN substrates. The buffer layers for these non-polar devices comprised of thick low defect GaN layers which were deposited using a unique selective area lateral epitaxial (SALE) procedure. The materials growth and device characterization results for the polar and the non-polar LEDs will be compared to discuss the role polarization plays in III-N devices.


Although LEDs emitting below 300 nm are desired for fluorescence and imaging, high optical, electrical and device performance is challenging. Several groups have demonstrated shallow donor n-type AlGaN LEDs emitting below 360 nm. However, for high Al GAN films, both n-type and p-type doping becomes increasingly more difficult as the Al concentration increases. This low doping efficiency combined with low mobilities and high sheet resistance, makes it particularly difficult to efficiently inject carriers into deep UV LED active regions. In order to address these materials issues we have developed a flip chip LED process where interdigitated contacts are used to reduce lateral device spreading and improve overall device efficiency. These contacts have been applied to LED die with emitting areas as large as 1 mm2. Deep UV LED wafers were grown by metalorganic chemical vapor deposition on sapphire substrates beginning with a low temperature AlN nucleation layer followed by a 47% AlGaN base layer. In one design, the LED active region consisted of three A0.85GaN/Al0.15GaN quantum wells with Al0.85GaN/Al0.15GaN barriers which showed LED emission over a range from 280 to 300 nm. The LED was capped with a 500 Å-thick Al and 4 GAN n-type buffer followed by 500 Å thick p-type GaN for use as a contact layer. Devices were flip-chipped to Si or SiC substrates and UV photoluminescence were emitted through the transparent AlGaN p-type base layer and sapphire substrate. LEDs showed continuous wave output powers as high as 140 µW at 130 Å/cm2 with voltages on the order of 12 volts at 20 mA. Recent device performance results for various AlGaN-based QW active regions will be presented. Critical performance issues for both understanding and improving device performance including the competition between quantum well emission and deep level emission, current spreading, light extraction and thermal management, will be discussed.

Sandia is a multiprogram laboratory operated by Sandia Corporation, a subsidiary of Lockheed Martin Corp. for the United States Department of Energy under Contract DE-AC04-94AL85000.

11:15 AM 4Y1.8 High Power 280 nm AlInGaN UV LEDs in the High Injection Regime, Maria Gheasainov, J. Sti., G. Cui, J. Han, H. Peng, E. Makarova, Y. He, Y. He Song and A. V. Nurmi, 1 Electronic Engineering, Yale University, New Haven, Connecticut, 2 Division of Engineering, Brown University, Providence, Rhode Island.

We report on the performance of AlInGaN LEDs, aimed at high power operation in the 280 nm wavelength range. Quaternary AlInGaN multiple quantum well active regions are embedded into AlGaN p-n diodes, which are grown on AlN buffer layers on sapphire substrates. Circular devices with diameters of 100 mm and below have been evaluated, with emphasis on testing the performance limits in the high power, pulsed injection regime. Under CW conditions, typical internal radiative efficiencies exceeding two percent have been achieved from LEDs that show clean emission spectra centered around 280 nm. Devices with residual n-type carrier density of 1 x 1018 cm-3 and 1 x 1019 cm-3 and p-type carrier density of 1 x 1017 cm-3 and 1 x 1019 cm-3 have been evaluated. The current density limits of devices fabricated in the lab are 30 A/cm2 and 40 A/cm2, respectively. The robustness of the devices has been verified under pulsed injection (10 usec-1 usec) at current densities in excess of 10 kA/cm2 where UV output densities direct-coupled off a phaser device up to tens of Watts/cm2 have been measured. Both growth and device design parameters affecting LED performance will be presented.

11:30 AM 4Y1.9 Optical Properties of AlN/AlGaN/InN Short Period Superlattices - Deep UV Light Emitting Diodes and Photodetectors, Mark Holt, I. Ahmad, V. Kuryavets, B. Borisov, G. Kipshidze, A. Chimando, S. A. Nikishin and H. Tenkin, Texas Tech University, Lubbock, Texas.

We report electrical and optical properties of deep UV light emitting diodes (LEDs) and photodetectors (PDs). Devices are based on short period superlattices of AlN/AlGaN/InN x = 0.08 grown by gas source molecular beam epitaxy with ammonia. Structures consist of a 53 nm thick AlN nucleation/buffer layer deposited on sapphire. This was followed by a 14 nm thick Si-doped buffer layer of AlGaN or AlGaN/InN grown to be transparent for wavelengths beyond 240 nm. The design thickness of the superlattice well systems is systematically varied from 1.50 nm to 1.25 nm and the thickness of the barrier is varied from 0.76 nm to 2.00 nm. The n- and p-type SPSLs were doped with Si derived from silane and Mg evaporated from an effusion cell, respectively. Optical properties are investigated using reflectance, cathodoluminescence, and, in the case of LEDs, using electroluminescence. By controlling the properties of the superlattices, we obtain energy gaps ranging from 4.5 eV (276 nm) and 5.3 eV (234 nm). Electrical properties are studied using LV, CV, and Hall effect. LEDs based on these superlattices and operating in the range from 260 to 280 nm exhibit turn-on voltages in the range of 4 to 6 V and support dc current densities in excess of 500 A/cm2 at room temperature. The cutoff wavelength of PDs based on these SPSLs can be varied in the range of 340 to 280 nm by changing the barrier and well thicknesses. Performances for the LEDs and PDs described are further improved when considering the impact of the AlN/GaN interface. Influence of barrier/well thickness variations on the output power of the LEDs will be also discussed. This work is supported by DARPA, NSF (ERC-07020240 and ECS-0871290), US Army SRCCOM, and the J. F. Madasof Foundation.

11:45 AM 4Y1.10 High Performance Solar Blind Detectors based on AlGaN grown by MBE and MOVCD, Juan-Yueh Dubois1,2, Jean Luc Reverchon3, Mauro Mosca3, Nicola Grondjem1 and France Oomens2,3, CHRHEA-CNRS, Valbonne, France, 1 Device Department, Thales THT, Grisy, France.

Solar blind detectors based on AlGaN were fabricated and characterized. AlGaN heterostructures, with an active region with 45% Al and a window layer with 62% Al were grown on sapphire to allow for back side illumination. Both Molecular Beam Epitaxy and Metal Organic Chemical Vapor Deposition were used and led to similar results. Metal Semiconductor-Metal (MSM) and Schottky diode detectors have been fabricated. Photoresponse spectra were recorded and show solar blind characteristics with cutoff wavelengths in the range of 270-290 nm. The visible and near UV rejection ratio reaches 5 decades and the cut off slope is 4 nm per decade, which is the current state of the art for solar blind detectors. From MSM detectors, we used a two-level process where the contact pads are reported on a dielectric layer which allows to reduce the dark current to values as small as 1 x 10-10 A/cm2 for biases up to 21 V in a detector with a 2 mm finger spacing and an area of 2x10-5 cm2. The noise is below the detection limit. Extrapolations can be made from measurements performed at higher biases on devices with larger dark currents. They show that the noise is limited by the shot noise. The responsivity is in the range of 0.05 to 0.1 A/W. At 10 V, the dark current is about 1 A and the noise density is 1.8E17a/Hz. For a band width of 50 Hz, the noise current is thus 1.25E-16 A. With a responsivity of 0.05 A/W, the detectivity D equals 4E14/W corresponding to a noise equivalent power NEEP of 2x10-9 W. The noise is then related to a photon on flux of 500/µs which is among the best values ever reported in AlGaN solar blind detectors. The detection of the geometry [finger spacing and width] was studied, and we will use it to show the ultimate performance that can be obtained in AlGaN MSM detectors. Schottky diode AlGaN solar blind detectors exhibit a larger dark current due to parasitic leakage currents on the mesa edges. They however show a larger responsivity, so that high performance is also achieved in AlGaN solar blind Schottky diodes.

SESSION V2: Bulk/Quasi Substrates

Chair: Richard Mckee

Monday Afternoon, December 1, 2003

Room 312 (Hyne)

1:30 PM V2.1 Growth and Fabrication of 2 Inch Free-standing GaN
Substrates Via the Boule Growth Method, Drew Harris, Lianghong Liu, Ed Preble, Darin Thomas and Mark Williams, Kynma Technologies, Inc., Raleigh, North Carolina.

High-quality single crystal GaN substrates have been demonstrated using a boule growth process. Here we report on the crystalline boules that were formed during the growth process and their material characterization. Using a chemical vapor transport process, GaN crystals were grown at growth rates greater than 200 μm/hr. Boules greater than 3 mm thick were grown and processed into free-standing substrates. Rocking curve and X-ray diffraction were performed on the substrates with FWHM values of 92 and 146 arcsec for the [002] and [102] reflections, respectively. Cross-sectional TEM images and photoluminescence measurements indicate the presence of surface damage after mechanical processing, which is not effectively removed with a CMP process. ICP etching was used to remove surface damage and create a surface suitable for epitaxial growth. Atomic force microscope images show a surface roughness RMS value of 1 nm and a peak-to-valley value of ~15 nm, both of which approach values for commercially available sapphire wafers.

2000 PM Y23
Growth and Characterization of Bulk GaN Crystals at High Pressure/High Temperature, M. D. DePauw, Hoang Hong, Dong-Sil Park, Kristi J Narrings, Steven F LeBlanc, Philip R Twemlow, David R Clarke and Richard J Molian, GE Global Research Center, Niskayuna, New York; Materials Department, University of California, Santa Barbara, and Santa Barbara, California.

We report the growth and characterization of bulk GaN single crystals by temperature gradient recrystallization at high pressure and high temperature (HPHT), using apparatus adapted from that used to synthesize gem-grade diamond crystals. The bulk crystals are grown on seeds that were synthesized by hydride vapor phase epitaxy (HVPE) and subsequently cleaved from their sapphire substrates. The process is routinely able to grow crystals larger than 10x10 mm in diameter. The crystals are transparent and well faceted, and surface densities below 10^4 cm^-2 have been achieved. Additional characterization of the GaN crystals is also presented.

2:15 PM Y24
Preparation of A-plane Gallium Nitride Fabricated via Spontaneous Lift-off, Benjamin Allen, Edward J. Hinkley, Shigemasa Matsuda, Tetsuo Ruiji, Feng Wang, Paul F. Fini, Steven F. DenBaars and James S. Speck, Materials Department, University of California, Santa Barbara, California.

Nonpolar [11-20] a-plane gallium nitride has been found to grow heteroepitaxially on sapphire [11-20] a-plane sapphire by a number of groups. However, previous attempts to grow a-plane GaN on sapphire Al2O3 by hydride vapor phase epitaxy (HVPE) yielded faceted films that were unsuitable for subsequent device regrowth. Recently we reported on the first HVPE growth of planar a-plane GaN films on sapphire substrates. These films were characterized by smooth surfaces with RMS roughness values below 0.8 nm, but decorated by ~10^4 cm^-2 nanometer-scale pits and ridges marking threading dislocation termination sites and basal plane stacking faults, respectively. In this abstract, we report on lateral epitaxial overgrowth (LEO) of a-plane GaN, its effectiveness in eliminating both threading dislocations and basal plane stacking faults, and subsequent regrowth via spontaneous lift-off. The a-plane GaN regrowth process was performed in a three-zone directed-flow HVPE system at 1041°C and 0.77 Torr. Typical growth rates were 1.650 μm/hr with V/IH ratios of 15.0. The masks for the LEO process were prepared by utilizing conventional photolithographic processing and wet etching to ~130 nm-thick plasma-enhanced chemical vapor deposited SiO2 dielectric layers. A variety of mask geometries were found to yield planar, recrystallized films, including an array of parallel stripes denoted along the GaN [1<020], [01<20], and [001] directions. In each case, atomic force microscopy showed a reduction of the surface pit density to less than 3 x 10^4 cm^-2 and RMS roughness values below 0.7 nm. The overgrown material in the GaN [1<020] wings for [1<020]-oriented stripes was found to have threading dislocation and basal plane stacking fault densities of less than the transmission electron microscopy resolution limits of 5 x 10^4 cm^-2 and ~10^3 cm^-2, respectively. Cation luminescence studies of the LEO films showed a four-fold increase in band edge luminescence intensity in the overgrown material compared to the window material. The above-described LEO process has been utilized to fabricate free-standing a-plane GaN films for the first time through spontaneous lift-off. In addition to providing defect reduction, a-plane GaN films grown laterally from [1<020]-oriented stripes spontaneously separate from the substrate upon cooling. Thermal expansion-related stresses in the overgrown material exceed ~10^-7 m/m at room temperature. Virtually no adhesion exists between the laterally overgrown GaN and the sapphire material, and separation occurs consistently in the window material between the SiO2 stripes. The a-plane GaN films spontaneously peel off from the outer edges of the wafer to relieve the bowing stresses. Nearly full two-inch wafers have been produced by this process with film thicknesses of 125 μm by this process.

3:00 PM Y25
Selectivity Area Lateral Epitaxy of A-Plane GaN Layers and Heterostructures on SiC Substrates, Jiwon Yang, Jinhyung Zhang, Wenhong Sun, Miklós Govesk, Edmundo Kukutis, Vinod Adwanhhan, Shiu Rua, Shunli Wu, Hongmei Wang, Zheng Gong, Ming Su and M Asif Khan, Dept. of Elect. Engr., Univ. of South Carolina, Columbia, South Carolina.

To date nearly all nitride light emitters employ c-orientation heterostructures that possess strong electrostatic fields parallel to the [0001] direction. These internal fields severely limit the luminescence due to electron and hole wave functions. In this work, we report an innovative selective area lateral epitaxy (SALE) approach to deposit high quality low defect density [1<020] GaN films on non-polar a-plane sapphire substrates. The fully covered SALE a-plane GaN films exhibit smooth surface (RMS roughness of 0.45nm), superior structural quality (FWHM of [1-20] oomega scan of only 0.89 degree), as well as excellent optical quality (threshold for stimulated emission 100kW/cm2). Non-polar AIGaN/GaN, InGaN/GaN as well as AlGaN/InGaN multiple quantum wells were then grown on the SALE films. The light emission intensities from these heterostructures were at least one order of magnitude higher as compared to the MQWs which were deposited on the n-plane GaN films grown by the conventional MOCVD process. Therefore, our new SALE growth procedure provides an excellent approach for producing non-polar nitride films and heterostructures for high efficiency optoelectronic devices.

2:45 PM Y26
Recent results on vapor phase epitaxial and bulk growth of GaN and AIN materials, Vladimir A Dmitriev, Yuri V Melnik, Alexei Pchelnikov, Oleg Kovalenko, Vitali A Shrkhovnik, Oleg Lednev, Vladimir Sazov, Yelena Shapovalova, Vladimir A Ivanov and Alexander Ukoiv, TDI, Inc., Silver Spring, Maryland.

In this report we summarize our recent results on development of vapor phase growth technology for group III nitride semiconductor materials. Material properties of GaN, AIN and AIGaN epitaxial layers grown by hydride vapor phase epitaxy (HVPE) will be presented including properties of thick [up to 70 microns] crack-free AIN layers on 2-inch SiC substrates, AIN layers on 4-inch Si substrates, and GaN layers with reduced dislocations grown on 4-inch sapphire. Multi-layer HVPE grown AIGaN/GaN and AIGaN/AlGaN used device structures for transistor and light emission applications in a wavelength range from 310 to 340 nm will be described. Second aspect of the report is growth and characterization of bulk single crystal materials from vapor phase. We will present the latest experimental data on material properties of GaN, AIN, AIGaN wafers fabricated from bulk crystals and initial results on homoepitaxial growth on these wafers.

3:30 PM Y27
Aluminum nitride, because of its high thermal conductivity, UV transparency, and low dielectric constant, is of great interest for electronic and photonic applications. Large diameter single crystal AlN wafers have commercial potential as substrates for GaN and AlGaN-based devices. However, the existing substrates are either too small in diameter or deposited on expensive non-native substrates, such as silicon carbide. The Halide Vapor Transport Epitaxial (HVTE) process, described here, was developed to overcome the present wafer deficiencies. To avoid the disadvantages of the conventional methods, we have used AlN and NH3 as reactants to grow AlN MOVPE on silica substrates with used to seed the HVTE growth. The influence of the deposition and adduct temperature, reactor pressure and gas flow velocities on the layer growth rate and crystal quality was investigated. The ranges of interest were mainly the high deposition temperatures (1000-1300 °C), the low adduct temperature (50-500 °C) and higher velocities from 300 to 400 scm. Single crystal AlN layers 2 inches in diameter and with thicknesses up to 50 μm have been grown with a deposition rate of 10-20 μm/h. The layer quality, as determined by x-ray rocking curve measurements (with a high resolution Philips instrument using omega scan), will be discussed. The FWHM for (002) and (102) planes are in the range of about 300 and 500 arcsec, respectively, replicating the linewidths of the MOVCVD templates. With trace element impurity measurements by SIMS analysis indicated about 10 ppb of oxygen and a negligible carbon contamination, the electrical properties remain insulating. Tests are under way to evaluate this material as a substrate for GaN-based devices.

3:45 PM Y2.28
Vapor phase transport of AlN in an RF heated reactor: Low and high temperature studies. Vladimir Novak 1, R. Schlessier 2, Zhe Si 3, S. Mahmud 3 and Stephen Beaudoin 2.
1Department of Materials Science and Engineering, North Carolina State University, Raleigh, North Carolina, 2Department of Chemical and Materials Engineering, Arizona State University, Tempe, Arizona, 3School of Chemical Engineering, Purdue University, West Lafayette, Indiana.

AIN crystals were grown by vapor phase transport in an RF heated sublimation reactor. The studies were performed with two main goals: (1) to optimize the initial nucleation stage of single crystal growth on AIN-coated SiC (seeded growth), and 2) to improve the growth rate by investigating the mass transfer effects in the high temperature range from 2000-2400°C. The effects of temperature, source-to-substrate distance and the growth rate in the lower temperature range were investigated. A one-dimensional mass transfer model based on equilibrium sublimation and gaseous diffusion was developed. Model parameters were estimated from growth experiments carried out at a nitrogen pressure of 600 Torr, a nitrogen flowrate of 100 scm and temperatures from 2000 to 2550 °C. The model was validated against independent growth experiments conducted between 2000 and 2400 °C, with growth rates of 1 mm/arc of 25 mm diameter and 12 mm long polycrystalline boules. The seeded growth nucleation studies were conducted at temperatures ranging from 1800 to 2000 °C, while all other parameters were the same as in the high temperature studies. At lower temperatures (1800-1850 °C) and large source-to-substrate distance (~35 mm), discrete single crystal growth was observed with few instances of coalescence. Higher temperatures (1850 °C), short source-to-substrate distance (~10 mm) and longer growth times (~360 hrs) yielded better crystal coalescence. After the nucleation stage, the observed growth rates were in agreement with the predictions of the growth model developed above for gaseous mass transfer-controlled growth of polycrystalline boules. Optical and electron microscope images of the seeded crystals revealed step-flow growth while the x-ray analysis confirmed the single crystal nature of the grown material. Transport and essentially colorless single crystals were grown over surface areas of 2in x 2in.

4:00 PM Y2.29
Influence of Crucibles on AIN Bulk Crystal Growth. Rafael Dalmau, R. Schlessier and Z. Si.
Materials Science and Engineering, North Carolina State University, Raleigh, North Carolina.

Growth of AIN single crystals by sublimation of AIN powder was carried out in a resistively heated reactor at temperatures up to 2300 °C. Experiments were performed in nitrogen atmosphere at pressures ranging from 400 to 1000 Torr and 100 scm gaseous flow. A variety of crucible materials, such as BN, AIN, W, Ta, TiN, and Nb were evaluated. Our studies have shown that the morphology of crystals grown by spontaneous nucleation strongly depends on the growth temperature and reactor. Crucible selection and a profound effect on contamination in the crystal growth environment, influencing nucleation, coalescence, and crystal morphology. Crystals grown in BN crucibles exhibited highly anisotropic growth rates along different crystallographic directions. Crucibles made of refractory metals, such as tungsten, yielded well-oriented single crystals with isotropic growth rates. Depending on the choice of reaction crucible, crystals were optically clear or tinted orange. Orange coloration was observed in crystals grown in refractory metal crucibles. Spontaneous nucleation of gaseous AlN crystals up to 15 mm in size were characterized by x-ray diffraction (XRD), transmission electron microscopy, x-ray topography, and SEM. Average density distributions were on the order of 1000 g/cm3, with extended areas virtually free of foreign matter, while high-resolution XRD showed rocking curves as narrow as 7 arcsec. A survey of the influence of reaction crucibles on crystal growth and morphology, as well as characterization data, will be presented.

4:15 PM Y2.10
Growth of GaN crystals under ammonothermal conditions. Bogo Wang, Michael J. Callahan, David F. Bliss and Joseph W. Koziol. 1Department of Chemistry, Clemson University, Clemson, South Carolina, 2SNHC, Air Force Research Laboratory, Hanscom AFB, Massachusetts.

Growth of GaN bulk crystals under ammonothermal conditions have been developed. The experiments were performed at 500-600 °C, 30 ~ 45 kpsi from ammonia solutions in Rens/ autoclaves for up to 3 weeks. Nutrients were polycrystalline GaN made from vapor phase transport growth. Single crystal clusters of GaN on the order of 50 μm - 1 mm long were obtained. These crystals were spontaneously nucleated on the lower walk of the autoclaves. Transported growth on polycrystalline seeds from vapor growth at up to 100 μm per day was also achieved. The ammonothermal growth and the x-ray diffraction. The growth mechanisms will be discussed.

4:30 PM Y2.11
Curvature and strain in thick HVPE-GaN for quad-substrate applications. Claudia Roder, Tim Boettcher, Detlef Himmel, Torben Pankova and Bo Menzemer. 1Inst. of Solid State Physics, University of Bremen, Bremen, Germany, 2Department of Physics and Measurement Technology, Linköping University, Linköping, Sweden.

In order to overcome the major problem in the GaN technology, namely the lack of a native substrate, the most promising approach is the fabrication of thick GaN on sapphire using hydride vapor phase epitaxy. In combination with the laser liftoff technique, freestanding GaN films were demonstrated. However, a critical remaining question arising from the thermal and the lattice mismatch is the accommodation of strain and wafer bending during growth and during cooldown, both of which cause the cracking of the freestanding substrate. To access the strain state at room and at growth temperature, temperature-dependent X-ray diffraction up to 1000 Kelvin was utilized to determine the lattice constants as well as the wafer curvature in situ. The simulation of the freestanding GaN on the individual strain components, namely the intrinsic, thermal strain as well as the intrinsic growth and hydrostatic strain. In agreement with previous findings, all samples investigated were found to be under biaxial tension at growth temperature, which is presumably caused by the high temperature incoherent coalescence. Upon cooldown, the thermal strain overcompensates the intrinsic, growth strain, such that at room temperature the film is under biaxial compression, while the substrate is tensile strained. In addition, the wafer bending reduces the tension at the GaN/sapphire interface, such that at a critical thickness cracks nucleate due to the tensile stress of sapphire. One solution is to increase the thickness of the sapphire substrate, which reduces the wafer bending and raises the critical thickness for crack appearance. To quantify the hydrostatic strain, GaN layers of varying thickness grown on sapphire as well as freestanding GaN were measured, since a gradient of the hydrostatic strain might explain the curvature of freestanding material after lift-off. All measurements were in good agreement with quantitative simulations of the stresses at the various interfaces.

4:45 PM Y2.12
Lateral growth of GaN is used in a variety of related techniques to produce lower dislocation densities than currently possible with direct GaN growth onto common silicon or sapphire substrates. Research has focused on bending dislocations from initial GaN growth into the substrate plane where they are presumed to annihilate, terminate at a free surface, or are at least concentrated into initial growth and coalescence regions. It has also been noted that wing tips result in tilt boundaries of dislocations upon wing coalescence, which could be a substantial source of dislocations in otherwise high-quality materials. In this report, we discuss the dislocation dynamics occurring after dislocation bending in coalescence materials. Secondary dislocations of dislocation are observed to form what are believed to be tilt boundaries necessary to accommodate wing tilt, or in some cases are distributed throughout the wings to create sliding systems. The observed number of dislocations is generally insufficient to fully account for the wing tips, i.e., some of the wing tilt is accommodated elastically. In samples with wing tips ranging from 0.2 to 2 deg, the elastic tilt is estimated to be +15 deg. We propose a model analogous to the concept of a critical thickness for a line of dislocations, where there is a critical tilt that is always accommodated elastically. The model suggests that tilt boundary dislocations can be avoided altogether if the wing tips can be reduced below the critical tilt. Another source of secondary dislocations are defects in the wing coalescence interfaces that punch out dislocation loops in the o-plane. The threading dislocations over cantilever ‘posts’ have been observed to pin dislocation loops, i.e., we propose that the Cottrell mechanism acts to limit the size of the dislocation loops. The strength of the Cottrell mechanism in limiting dislocation loop decreases as the density of the forest of perpendicular threading dislocation decreases, which means that wing tip dislocations can be very large in samples with otherwise very low dislocation density. Elimination of both types of secondary dislocations is of interest for practical device applications: tilt boundary dislocations occur in every wing and dislocations below them may be required for compensation on a microscopic scale, can represent a substantial defect density on the scale of a modern GaN device. These models for dislocation dynamics are not specific to cantilever epitaxy and should apply to other techniques using lateral growth of GaN. Therefore, reducing wing tips to below a critical tilt and eliminating the formation of dislocation loops at the wing coalescence interfaces are two important challenges to obtaining truly low dislocation density in laterally-grown GaN devices.

SESSION Y3: Hereto-mepays
Chair: Theodore Moustakas
Tuesday, Morning, December 2, 2003
Room 312 (Hynes)

8:30 AM *Y3.1
GaN-based Epilayers and devices on Silicon, Alios Jakob Kress
1Institute of Experimental Physics, Otto-von-Guericke University Magdeburg, Magdeburg, Germany
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Since 15 years silicon as a substrate has attracted much attention for the epipatal growth of III-V compounds like GaAs and InP because of its unique physical properties, low price and its availability in large diameters up to 12 inches now. From the point of view of electronics Si offers a low price way compared to sapphire. (SiC, high crystalline perfection, availability of large size substrates, all types of conductivity, and high thermal conductivity. Furthermore, it can be easily processed. However, in spite of huge efforts, no real breakthrough has been obtained because of the high mobility of dislocations in GaAs and InP leading to a rapid degradation of all devices fabricated so far. In contrast, GaN-based devices are known to operate very well without aging effects with dislocation densities as high as 10^10 cm^-2. Thus, in case of a successful growth of GaN on Si, GaN-based electronics and optoelectronics as well as the integration of Si and GaN-based devices on the same chip becomes feasible. The growth of device-quality GaN on Si is known to be limited by severe stress problems leading to a wafer bending and to cracked layers when exceeding ~1 micronmeter in thickness. Using an in-situ optical sensor for monitoring the wafer curvature we distinguished and controlled several origins of residual stresses during growth: epipatal stresses due to mismatch of internal stresses, e.g. compressive when inserting on AlN interlayer, thermal stresses due to the difference between the film and substrate thermal expansion coefficients (tensile), Si and Mg-doping (tensile), grain boundary relaxation during coalescence of 3D islands (tensile), interaction of substrate with both GaN mask (compressive). Remarkably, the tensile stress for S-doped GaN cannot be explained by a simple change of interatomic distances but is likely connected to the dislocation density. By an appropriate balance of all these contributions cracking narrowing of the substrates can be avoided. With the insertion of thin AlN interlayers and in-situ SiN film masks, we succeeded in growing 4 micronmeter thick, crack-free, planar GaN on Si. Latest results on FET and LED device structures based on such layers will be presented.

9:00 AM *Y3.2
Achieving High Quality AlN Epilayers: Epitaxial Growth, Optical Transitions, and Impurity Properties, Min Lal Nknami, K-Isho Namb, Neeraj Nigam, Jing Li, Kyoong Hoon Kim, Jeungsun Jin and Hangyong Jeong, Physics, Kansas State University, Manhattan, Kansas.

Knowledge concerning the optical properties of AlN is very scarce, despite its importance for high-quality heterostructure and nitride semiconductor properties as well as for device applications. With its large direct bandgap (around 6 eV at room temperature), high thermal conductivity and hardness, and high resistance to chemical reactions, AlN has many attractive properties and many important applications such as UV emitters for the detection of biological and chemical agents and for general lighting. Here, we report the MOCVD epitaxial growth and deep UV time-resolved photoluminescence (PL) study of high quality AlN MBE layer. Important properties concerning the energy bandgap, the free and bound exciton binding energies and decay lifetimes have been measured. Mg and Si doping in AlN was investigated. From PL emission spectra and the temperature dependence of the PL emission intensity, a binding energy of 0.51 eV for Mg acceptor in AlN was determined. Together with previous experimental results, the Mg acceptor activation energy in AlGaN-xN as a function of the Al content (x) was extrapolated for the entire AlN composition range. The average hole effective mass in AlN was also deduced to be about 2.7m0 from the experimental value of the Mg binding energy together with the use of the effective mass theory (assuming a dielectric constant of 8.5). Although Mg acceptors are an effective mass state in ultralight AlN, the MBE growth of this large acceptor binding energy of 0.51 eV, only a very small fraction (about 10-9 or one billionth) of Mg dopants can be activated at room temperature in Mg doped AlN, implying that it is extremely difficult to achieve p type AlN by Mg doping. Si doping induced PL emission linewidth broadening and band gap renormalization effects have also been observed. The role of oxygen impurities in determining the optical and electrical properties of AlN has been investigated.

9:15 AM *Y3.3
HNO3 treatment of substrate substrate for management of GaN polarity in MOCVD method, Motoki Tsukuba, Masanori Sumiyama1,2 and Shonny Puke3, 1E&E Eng, Shinshu University, Hamamatsu, Japan; 2CREST-JST, Tokyo, Japan.

We discovered that HNO3 treatment of a c-plane substrate substrate for management of the polarity of GaN film grown by MOCVD. A substrate substrate was treated in HNO3 solution at room temperature after cleaning it in H2-flush at 1800°C. When GaN film was grown on the treated substrate by conventional two-step growth in MOCVD, it had N-face [-N polarity, having hexagonal facetted surface. GaN film grown on a HNO3-treated substrate without the HNO3 treatment had G-face [+-G polarity, having smooth face, even though the substrate was exposed to air. By using this treatment, we have attempted simultaneous growth of GaN film with both polarities on a divided area of a single substrate. After the H2 cleaning in the growth heater, a mask pattern of photoresist was formed on the HNO3-treated substrate, and then the masking was done in H2 for 10 min. After removing the mask pattern, the substrate was introduced into the reactor again, and GaN film was deposited on it by two-step MOCVD method. GaN film with hexagonal facets and smooth surface on the other region was simultaneously grown on HNO3-treated and the other region of the substrate, respectively. It was confirmed that only region of hexagonal facets was etched by KOH solution. We successfully achieved the simultaneous growth of GaN film with both polarities. This indicated that the polarity-controlled GaN film would be managed on a single substrate.

9:30 AM *Y3.4
Step-Flow and Layer-by-Layer Growth of GaN on Si(0001) by Molecular-Beam Epitaxy, Jun Suda1,2, Norio Onoimam1,2, Tsunenobu Kimoto1 and Hiyuki Masumilani1,2, 1Department of Electronic Science & Engineering, Kyoto University, Kyoto, Japan; 2Nanostructure and Material Property, PRESTO, Japan Science and Technology Corporation (JST), Kawaguchi, Japan.

Growth of high-quality AlN on a Si substrate is one of key issues to realize high-performance GaN-based high-power high-frequency heterojunction field-effect transistors (HFETs) and AlN/Si met-al-insulator-semiconductor FETs (MISFETs). We have investigated precise control of AlN/Si(0001) surface and optimization of growth conditions of AlN in molecular beam epitaxy (MBE). Recently, we have realized RHEED intensity oscillation just after the growth of AlN on SiC with high reproducibility [1]. In this study, we focused on the correlation between growth kinetics and crystalline quality of AlN growth layer. 4H-SiC(0001) c-face substrate was grown by high-temperature HCl-gas etching to move a surface damage
layer and obtain 4 ML or 6 ML-height step-and-terrace structure. Next, substrates were dipped into HF solution for oxide removal and then loaded into the growth system. In this GaAs-deposition and flash-off were carried out, which results in an oxygen-free (sgr 3x sgr 3R30°) GaN. In this paper, we report the results of the AlGaN grown by MBE. Growth in this paper. The FWHM of low-temperature GaN film is an important measurement for the quality of the grown film. Therefore, we have performed experimental and theoretical studies of the surface reconstruction of GaN films. The AlGaN films are grown on Si-face 6H-SiC substrates or MOCVD-grown GaN on sapphire substrates by plasma-assisted molecular beam epitaxy (PA-MBE). The AlGaN film quality is found to be good in terms of the crystalline quality

9:45 AM **V.3.5** Growth and Surface Reconstructions of AlN (0001) Films. Chie-Deok Lee1,2, Randall M. Feenstra1, John E. Northrup2 and Joerg Neugebauer1,2,1Physics, Carnegie Mellon Univ., Pittsburgh, Pennsylvania, 2Palo Alto Research Center, Palo Alto, California, 3Fraunhofer-Institut für Materialphysik, Freiburg, Germany; 4Rutgers RF Components, Andover, Massachusetts.

AlN is considered to be a useful semiconductor material for high temperature and high power electronic devices and also optoelectronic devices. While there has been progress in identifying surface structural arrangements on GaN, there is currently only limited knowledge about the surface structures of AlN. Therefore, in this work, we have performed experimental and theoretical studies of the surface reconstructions of AlN films. The AlN films are grown on Si-face 6H-SiC substrates or MOCVD-grown GaN on sapphire substrates by plasma-assisted molecular beam epitaxy (PA-MBE) to obtain AlN polycrystals for Si-face 6H-SiC surfaces. Surface reconstructions of AlN films are studied using high-resolution transmission electron microscopy (HRTEM) and X-ray diffraction (XRD) techniques. The AlN films are grown on Si-face 6H-SiC substrates or MOCVD-grown GaN on sapphire substrates by plasma-assisted molecular beam epitaxy (PA-MBE). The AlN films are grown on Si-face 6H-SiC substrates or MOCVD-grown GaN on sapphire substrates by plasma-assisted molecular beam epitaxy (PA-MBE). The AlN films are grown on Si-face 6H-SiC substrates or MOCVD-grown GaN on sapphire substrates by plasma-assisted molecular beam epitaxy (PA-MBE).

10:30 AM **V.3.6** High-Quality AlN Epitaxial Films Grown using MOVPE and Their Applications. Masahiro Tanaka1, Takamichi Shibata1, Keisicho Arai1, Shigeaki Shinmy1, Masahiro Sakai1, Hiroki Katsukawa1, Osamu Odai1, Hideo Miyake2, Kenjuji Hiramatsu2, Hisayasu Hikawa1, Takashi Egawa1, Takashi Jimbo1 and Shigeo Hara1,1Fujitsu Laboratories Ltd., 2NTT Basic Research Laboratories, Japan.

AlN has piezoelectricity and is the widest direct band gap (3.3 eV) of the HILP nitride materials so that the realization of high-quality AlN epitaxial films can widely extend application fields of ILN nitride materials. So far, we have been growing AlN epitaxial films on several semiconducting substrates using metal organic vapor phase epitaxy (MOVPE) for various applications including surface acoustic wave (SAW) devices, optoelectronic devices and electronic devices. In order to realize SAW devices, a (11-20)-facet AlN epitaxial film on a (1102)-facet substrate is the most promising orientation due to its modest electromechanical coupling coefficient (1.5%) and its high SAW velocity (6800 m/sec). Using off-angle substrate substrates, in which their surface plane is tilted towards [1-10] sphaleritic direction, has been reported to improve the 6H-SiC substrates with high AlN growth, which can be applied to wide range of semiconductor devices. We have achieved crack-free high-quality AlN epitaxial films with an atomically flat surface on both substrates. The AlN epitaxial films have very low X-ray rocking curves for 300 ML thick films that correspond to full width at half maximum (FWHM) values equal to less than 80 arcsec. density of the AlN epitaxial films is as low as 1×10^{11} cm^{-2} and most of dislocations consist of edge-type. The FWHM value of AlN films grown on 6H-SiC substrate are equal to less than 200 arcsec and the AlGaN films have no cracks in all AlN multilayer range. In particular, dislocation density of AlGaN grown on GaN buffer is reduced below 5×10^{10} cm^{-2}. The improvement of crystal quality of the overgrown AlGaN layers improves some device performance, such as luminescent efficiency of LED, electronic properties of HEMT devices and so on.

11:00 AM **V.3.7** Growth Evolution of Gallium Nitride Films on Stepped and Step-Free Silicon Carbide Surfaces. C.R. Eddy, J. C. Colburn, M. E. Twigg1, R. T. Holm1, R. T. Henry2, P. G. Neudeck3, A. J. Trunck2 and J. A. Powell1,1Electronic Science & Technology Division, U.S. Naval Research Laboratory, Washington, District of Columbia, 2NASA Glenn Research Center, Cleveland, Ohio, 3Oakland University, Auburn, Michigan. Silicon carbide (SiC) is rapidly becoming the substrate of choice for high-power and high-temperature electronic devices employing the III-V nitride family of materials. This heteroepitaxial growth system continues to receive considerable attention as materials issues remain a fundamental limiter to device performance. The heteroepitaxial growth of gallium nitride (GaN) thin films on stepped and step-free 4H SiC surfaces is reported. Step-free SiC surfaces are created at a pattern of a SiC wafer and then epilayed on a substrate consisting of the same thicknesses (no interruption for AFM) and TEM analysis of both samples.

11:15 AM **V.3.8** GaN Nucleation Layer Evolution On Sapphire During The Ramp From Low To High Temperature. Daniel D. Koleske, Michael E. Colvin, Karen C. Cross, Christine C. Mitchell and Andrew A. Allerman, Organ, 11th Space National Laboratories, Albuquerque, New Mexico.

Despite the progress in the MOCVD growth of GaN, detail on how the nucleation layer (N.L.) evolves from high temperature (T) is not entirely understood. In this presentation we report on optical reflectance and AFM measurements of GaN N.L. evolution during the ramp and on the effect of the N.L. morphology changes from a continuous 30 nm thick layer composed of 20 nm sized crystals to a discontinuous layer containing nuclei that approach 200 nm in height and 500 nm in width. Further annealing of the N.L. causes a decrease in size and height of these large nuclei due to the formation of smaller nuclei in these large GaN nuclei is explained by NL decomposition [1] and subsequent re-formation of the gas phase GaN atoms onto the growing nucleus. Evidence for this mechanism is obtained from the height-height correlation functions [2] measured from the AFM images of the annealed nucleation layers as well as direct measurements of the GaN N.L. decomposition kinetics using optical reflectance [1]. From the AFM images up to 1/3 of the GaN from the original N.L. is removed, and the remaining GaN nuclei during the T ramp, however once the original N.L. is fully

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decomposed, the large GaN nuclei undergo decomposition resulting in smaller nuclei. Based on details of the decomposition kinetics and NL roughness, a three-dimensional reflective interference pattern is presented. Contributions of the surface diffusion, bulk diffusion, and decomposition and re-incorporation mechanisms to GaN NL evolution will be discussed along with how annealing conditions influence the evolution process. Guidance for optimizing growth of thin Ni films for use in GaN is also presented.

1:30 AM Y2.0

We report on the growth of n-type ZnO on p-type AlGaN and describe the performance of n-ZnO/p-AlGaN heterojunction light emitting diodes (LEDs). The n-type ZnO thin films are grown by MBE on (0001) sapphire substrates as epitaxial GaN buffer layers and Mg doped p-type AlGaN epitaxial layers of 12% Al content are grown by hybrid vapor phase epitaxy. Then, Ga doped n-type ZnO layers are grown on the AlGaN using plasma assisted chemical vapor deposition. The n-type ZnO and Mg-doped n-type AlGaN layers are separated by a thermal vacuum deposition of Al and Ni, respectively. LV characteristics clearly show rectifying diode-like behavior with a threshold voltage of 3.2 V and intense ultraviolet electroluminescence with peak emission at 390 nm, is observed under forward bias. The dominant emission mechanism is found to result from hole injection from the p-type, AlGaN into the n-type ZnO. This is a likely outcome since energy band diagrams built using the Anderson model show a much smaller barrier for holes in comparison to that which exists for electrons. The dependence of EL spectra on temperature was also measured and significant emission at up to 60 K was observed. The stability of device performance at high temperature indicates possible applications in harsh environments. With further development, it may be possible to fabricate UV laser diodes, with low, "excitonic" thresholds and high-temperature capability, by exploiting the thermal stability of the ZnO exciton.

11:45 AM Y3.10
Electrical and optical characteristics of delta doped AlGaN cladding layer materials for highly efficient 340nm ultra violet LEDs. Jeong-don Pyun, Huekk Song, Don Chang

SESSION Y4: Nanostructures
Chair: Yashiro Arakawa
Tuesday, December 2, 2013
Room 312 (Hyrs)

1:30 PM Y4.1
Effects of growth interruption on the structural and optical properties of GaN self-assembled quantum dots. Kyusuyuki Hoshino, Satoshi Kake, and Yashiro Arakawa, Research Center for Advanced Science and Technology, and Institute of Industrial Science, University of Tokyo, Tokyo, Japan.

We report the effect of growth interruption on the formation of GaN self-assembled quantum dots (QDs) grown by metalorganic chemical vapor deposition (MOCVD). GaN QDs are expected to realize highly efficient UV light emitters, due to quantum confinement effect and direct band-to-band luminescence. The photoluminescence (PL) from the QDs showed a redshift with increasing the growth interruption time. We found that the formation of the QDs is proceeding at the expense of the wetting layer grown on 6H-SiC (0001) substrate. Following the GaN QD formation, the growth was interrupted from 0 to 10 sec (0, 2.5, 5, and 10 sec). Then, a 20-nm-thick AlN capping layer was deposited. Two PL peaks were clearly observed in each sample with the interruption process at room temperature. One peak was observed around 4.8 eV and the other was due to the WL. The other core around 3.8 eV which originates from the QD structure. For no interruption time (0 sec), however, a strong single PL peak was observed at 4.1 eV. This peak can be attributed to the GaN quantum well signal. These results show that the two-dimensional/three-dimensional growth mode transition occurs during the initial growth interruption. The PL from the WL showed a blueshift with increasing the interruption time. This implies that the thickness of the WL decreases. In contrast, the PL from the QDs exhibits a redshift. These results mean that the size of the QDs increases at the expense of the WL, which is supported by AFM analysis of the uncapped QD samples.

1:45 PM Y4.2
Electron Field Emission from GaN Nanotip Pyramids Formed by Anisotropic Etching. Heck M. Ng, Jonathan Shaw, Aref Chowdhury and Nila G. Weinman, Bell Labs, Lucent Technologies, Murray Hill, New Jersey; Naval Research Laboratory, Washington, District of Columbia

GaN is of interest as a candidate material for electron field emitters due to its large breakdown field, resistance to radiation and low electron affinity. In general, electron emitter structures with sharp tips are utilized to take advantage of the field enhancement effect. In this work, we formed GaN nanotip pyramids by anisotropic-selective chemical etching after a patterned growth of GaN and Ni-Ga-GaN on (001) sapphire using plasma-assisted molecular beam epitaxy. The anisotropic etch was achieved by immersing the sample in a KOH solution which preferentially etches the N-polar GaN leaving the Ga-polar material intact. Pyramidal structures with sizes of (100) facets were formed in the N-polar regions. The density of the pyramids can be varied between 2 x 10^8 and 2 x 10^9 cm^-2, depending on the KOH concentration, etching duration and temperature. The tip diameter of the pyramidal structures were measured to be less than 20 nm. Field emission measurements were performed in a closed chamber using a stainless steel rod as the anode. The anode to sample distance was varied between 350 to 650 microns. The resulting current-voltage curves followed the Fowler-Nordheim equation. The turn-on voltage was taken to be the voltage at which the total emission current was equal to 1 nA. The turn-on field was estimated to be 1.6 V/μm which is in the best of our knowledge, the lowest reported value for unseeded GaN field emitters. The corresponding field enhancement factor was found to be 2200 ± 100 assuming a GaN work function of 3.5 eV. Results for lifetime measurements and cycled GaN pyramids will also be presented.
2:00 PM Y4.3

Gallium Nitride Nanowires as Optoelectronic Devices.
John Jacob Zengel1, R. Gupta2, K W Adz2, C P Beattie2 and P C Ecklund2,

Long gallium nitride nanowires (diam. ~10μm) have been synthesized by pulsed laser vaporization of a sacrificial layer of GaN and hydrogen gas. The resulting materials were characterized by Raman spectroscopy, scanning and transmission electron microscopy, and energy dispersive X-ray to confirm that the individual nanowires are wurtzite GaN single crystals with a [100] growth direction and have diameters and lengths on the order of 10 nm and 10 μm, respectively. Varicose methods were employed to investigate the effect of geometry and electron confinement in the nanowires of GaN. Our results on low-temperature Raman spectroscopy of GaN nanowires show that the Raman bands are broadened and downshifted as compared to the bulk. However, the size (diameter) of the nanowires is too large to exhibit any appreciable phonon confinement effects. We can understand and predict the results in terms of other effects such as compressive tensile stress. We also present results of other spectroscopic measurements such as FTIR and UV/VIS transmission and photoemission.

2:15 PM Y4.4

Influence of AlN Overgrowth on GaN Nanostuctures Grown by Molecular Beam Epitaxy.
Niek Goosen2, Eva Monroy3, Denis Johnstone2, Evrim Saygun3, Jean-Luc Hureau2 and Bruno Daubin2, DRFMC/SPPM/PSIC, CEA - Grenoble, Grenoble, France.

The use of nanostuctures in devices requires a precise control of the quantity of material deposited, and of the quality of the interface. It is generally assumed that the growth rate of thicker layers is not directly applicable in the nanoscale, where structures are particularly sensitive to decomposition, re-evaporation and diffusion. In the specific case of GaN nanostuctures in AlN: the influence of overgrowth of the properties of nanostuctures has not been addressed so far, although it is a crucial issue for the development of reproducible devices. In this work, we demonstrate that the thicker layer of GaN on AlN nanostuctures thickens during growth, and that the thickness of the AlN nanostuctures has a remarkable change in the dimension of the nanostuctures. Hence, the AlN quantum well thickness increases during AlN overgrowth. Regarding AlN quantum dots, capping implies an isotropic reduction of the island size. The thickness reduction has been measured by Rutherford Backscattering Spectroscopy (RBS) as a function of the GaN quantity. By combination of RBS, Transmission Electron Microscopy (TEM) and Reflection High Energy Electron Diffraction (RHEED), we demonstrate that the reduction of the nanostuctures occurs at the first stage of AlN overgrowth and it affects only the top GaN/AlN interface. The phenomenon is attributed to an exchange mechanism between Al nitrides from the capping layer and Ga atoms in the nanostuctures. The exchange is driven by the high binding energy of AlN as compared to GaN. We also demonstrate that this exchange is thermally activated and depends on the strain state of the nanostuctures. Finally, the Ga from GaN decomposition behaves as a surfactant that descends rapidly during the capping procedure. As a result, the interface between the AlN nanostuctures and the AlN capping layer is abrupt, with an interdiffusion layer thinner than one atomic layer, as measured from cross-section TEM images.

2:30 PM Y4.5

Intersubband Absorptions in Doped and Undoped GaN/AlN Quantum Wells Grown on Sapphire (0001), 6H-SiC or Silicon (111) Substrates.
Ann Helms1, Marie Thémy1,2, Akim Lusson1,2, François Julien1, Khalid Mourni3, Elisa Warde2, Eva Monroy2,3, Bruno Daubin2,3, Daniel Le Si Dang2 and Nicolas Grandjean1,2,1Action OptoGaN, Institut d’Electronique Fondamentale, CNRS/Université Paris-Sud, Orsay, France, 2CEA/CNRS Research Group "Nano physique et Semiconducteurs", DRFMC/SPPM, CEA/Grenoble, Grenoble, France, 3CIRHEA, UPR 10 CNRS, Valbonne, France.

Group III nitride heterostructures are treasuring new interesting because their huge conduction-band offset offers prospects for ultra-fast intersubband devices operating at fiber-optics telecommunication wavelengths. In this context, intersubband absorptions in the wavelength range of 1-1.45 μm as well as extremely short intersubband scattering times have been reported for n-doped GaN/AlN/GaN quantum wells grown on sapphire substrate using molecular beam epitaxy. In this talk, we report on the first detailed analysis of intersubband absorptions (IBS) in non-intentionally doped and doped GaN/AlN/GaN quantum wells grown by molecular beam epitaxy on either sapphire, 6H-SiC or silicon (111) substrates. The samples have been characterized by X-ray diffraction, Rutherford backscattering (RBS) and high-resolution transmission electron microscopy (TEM) as well as photoluminescence (PL) and Fourier transform infrared (FTIR) spectroscopy. Our results illustrate the results for n-doped GaN wells with strained AlN barriers grown on sapphire substrate. Room-temperature photo-induced absorption spectroscopy under irradiation by a 305 nm argon laser reveals IBS absorptions respectively peaked at 2.1, 1.85 and 1.45 μm for samples with an average well thickness of 1.86, 1.26 and 0.7 μm, as determined from RBS. Besides a larger broadening, similar results are obtained for samples grown on 6H-SiC or silicon substrates. Based on these calculations, we show that the strong electron absorption occurs in the layer plane at room temperature due to the combined effect of monolayer (ML) thickness fluctuations and the huge internal field. Moreover, the intensity thickness must be increased from the average value by 2 ML to account for the observed PL and IBS transition energies. Similar samples with GaN wells doped with silicon at 2×1019 cm-3 show an increased GaN growth rate with respect to n-doped samples. The IBS absorption is peaked at 1.85, 1.7 and 1.45 μm for doped wells with an average thickness of 2.1, 1.35 and 0.9 μm, respectively. With respect to n-doped samples, both the increased thickness and the smaller internal field due to carrier screening should lead to a red-shift of the IBS transition energy, which is opposite to observations. In order to understand the blue-shift of the transitions with doping, we have simulated the electron confinement in the quantum wells using an effective mass approach accounting for the screened internal fields, the GaN-conduction-band non-parabolicity and many-body effects such as the exchange interaction and the depolarization shift. For n-doped quantum wells, an excellent agreement with measurements is obtained assuming a GaN/AlN conduction band discontinuity of 1.28 eV and a polarization electron density of 3×1014 cm-2. Using PCs with thick AlN barriers, the electrical field is almost zero, and the carriers are free to move along all the layers. The results show that the IBS transition energy is inversely proportional to the conduction band discontinuity, and that the IBS transition energy decreases with increasing conduction band discontinuity.

2:45 PM Y4.6

III-Nitride Photonic Crystals for Blue and UV Emitters.
Tom N Odge1, Jagat Shikya2, Jingyu Lin2 and Hongxing Jiang3, Physics, Kansas State University, Manhattan, Kansas.

Photonic crystals (PCs) have attracted much interest as a means of enhancing light extraction efficiency in light emitting diodes (LEDs). A majority of the reports on enhancement in light extraction from LEDs using PCs have been on wavelength regions exceeding 700 nm and employing relatively large lattice periodicity in the PCs. Blue and ultraviolet (UV) LEDs based on III-nitride semiconductors are crucial for many applications but presently have very low quantum efficiency particularly for UV emissions. The need for the improvement of extraction efficiency in these LEDs is exceptionally great. We report the achievement of nanofabrication and characterization of triangular lattice arrays of PCs with diameter/periodicity as small as 100/180nm on InGaN/GaN multiple quantum well using electron beam lithography and inductively coupled plasma dry etching. Optical measurements on the PCs performed using near-field scanning optical microscopy showed a 60 degree angular variation periodic dielectric function, mainly between the propagation direction of emission light and the PCs lattice. Under optical pumping, a maximum enhancement factor of 20 was obtained for emission light intensity at wavelength as short as 475 nm at room temperature with an emission light peak at the same direction of the PCs lattice. The PCs array was subsequently fabricated on blue and UV nitride LEDs of wavelength 460 nm and 340 nm respectively, and electrically characterized. Light intensity was measured from the top surface of a phosphorless LED chip. A single layer injection using charge coupled device (CCD) camera and enhancement factor of 90%, 150% was observed. Implications of our results to nitride-based optical devices, particularly for further improving LED efficiency both for blue/green as well as UV emitters are discussed.

3:30 PM Y4.7

Structural and Optical Properties of GaN Quantum Dots.
Hassan Moumni1, Niek Goosen2, Christoph Adelmann, Evrim Saygun3, Eva Monroy2, Frederic Basard and Jean-Luc Rosovier1, DRFMC/SPPM, CEA, Grenoble, Grenoble, France.

One peculiarity of GaN/AlN heterostructures is the possibility to control their morphology by varying the metal/nitrogen ratio value. As the growth mode is directly related with the strain relaxation mechanism of nitride heterostructures, a simple tuning of growth parameters enables to grow either quantum wells (QW) or quantum dots (QDs), depending on the desired application. The Stranski-Krastanow (SK) growth mode is observed when depositing GaN/AlN in N-rich conditions. In this growth mode, the GaN film is grown on the GaN substrate by molecular beam epitaxy (MBE), and the TEM characterization of dots grown according to this growth mode will be presented. The modified Stranski-Krastanow growth mode takes advantage of the self-restraining effect of Ga observed when growing GaN in very Ga-rich conditions. In this mode, the Ga bilayer on the growing GaN surface leads to promote FVDm growth mode while inhibiting SK mode. However, interrupting growth under...
vacuum leads to the description of the Ga film, followed by a re-arrangement of the unstable 2D layer into 3D islands. A special emphasis will be put on the growth of GaN QDs with a N polarity, which have been grown on N-polar AlN deposited on C-polar 6H-SiC. The compressive strain experienced by GaN and, consequently, the stored elastic energy is expected to be exactly the same as in Ga-polar geometry. By governing both kinetics and surface energy, the priority of the reaction parameters in the 2D/3D transition both size and density of GaN islands have been comprehended, depending on the growth mode, modulation of SK and, depending on polarity, on GaN or GaN. The results suggest that the kinetic diffusion length is a key parameter governing the formation of GaN QDs. Accordingly, it will be shown that QD density can be controlled in the 10^10 - 10^13 cm^-2 range, depending on the growth/surface diffusion conditions.

**4:00 PM Y4.8**

**Optimization of GaN/AlGaN Quantum Wells for Ultraviolet Emitter Devices**

Andrews Haagleiter, Marco Greco, Daniel Fuhrmann and Uwe Rosewski. Institute of Technical Physics, Technical University of Braunschweig, Braunschweig, Germany.

Light emission by GaN-based heterostructures operating in the green, blue, and violet spectral region is known to be surprisingly efficient, while so far shorter wavelength GaN or AlGaN-based structures suffer from low quantum efficiency due to nonradiative recombination at defects. We have grown GaN/AlGaN quantum well structures on sapphire substrates using low-pressure MOVPE. After a low-temperature nucleation layer a 1 micron thick AlGaN buffer layer (about 25% Al) was grown, followed by a single or multiple GaN quantum well layers. The excitation of the QW's was varied in the 290-360 nm range by adjusting the QW width. From the data we estimate the polaron field to about 1 MV/cm. Using temperature dependence of photoluminescence we have determined the internal quantum efficiency (IQE) and analyzed its temperature dependence and compared the results to GaN/AlGaN QW's. For the GaN/AlGaN QW's we achieve remarkable IQE of in excess of 50%, only at fairly high excitation power, while GaN/AlGaN QW's provide IQE's of up to 46 % at a slightly lower power density, indicating a much stronger role of defects for the former. While thermal activation energies are dominated by defect-related mechanisms for GaN/AlGaN QW's, low activation barriers evident from the GaN/AlGaN data also hint at a more important role of defects.

**4:15 PM Y4.9**

**InN Nanostructures: Strain and Morphology**

Chine Pingjao1, Francois Demangeot1, Jean Brandolin1, Michel Caumont1, Olivier Brice2, Benoît Deshayes2, Sandra Char-Ruffaut2, and Bernard Gil2.

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We present an experimental work of wurtzite InN nanostructures grown on a GaN layer deposited on sapphire [0001] by Metal Organic Vapor Phase Epitaxy. InN quantum dots of controlled sizes have been fabricated by using specific growth conditions and taking advantage of self-organization that results from the 1/3 ratio between InN and GaN. For large InN dots, material quality assessment has been achieved by X-ray diffraction. Then dots of nanometric size as small as 25 nm in diameter have been fabricated, together with 2D layers. Islands larger than 300 nm have been characterized by using both atomic force microscopy (AFM) and micro-Raman spectroscopy. AFM measurements revealed that the current shape of the dots corresponds to truncated hexagons with a top surface diameter over base surface diameter of 1:3. The ordered ratio of the dot height (h) and d range from 0.07 to 0.04, which corresponds to rather flat nanostructures. The in-plane residual strain field have been evaluated by measuring the E2 phonon frequency shift in the micro-Raman spectra recorded from place to place across the dots. Careful analysis of these data makes clear that the dot aspect (e.g., the h/d ratio) is not a key parameter in determining the strain magnitude inside but rather the height of the dot, at least for the dots of up to 30 nm height and about 32 nm diameter. This further supports the notion that the dot shape is invariant as a function of the size, revealing a final stage of island formation. Nevertheless, the dot density is believed to decrease as a function of the dot thickness in the x direction, leading to the formation of relaxion, as predicted by the micro-Raman investigation. This conclusion is also reinforced by the increased strain measured in the facets of the dots in respect with its value in the dot centre. Finally, we gave evidence for the strain increase by capping the dots with a thin GaN top surface layer deposited at a rather low temperature, for preventing the thermal degradation of the underlying InN islands.

**4:30 PM Y4.10**

**Lateral Photocurrent Spectroscopy and Photoluminescence Investigation of the Effects of Disorder on the Excitonic Transitions in AlGaN/GaN Quantum Wells in Free**

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We report on the use of lateral photocurrent (LPC) spectroscopy as a simple and sensitive method to investigate the excitonic transitions in II-Nitride quantum wells. The technique is demonstrated on a 15 period AlxGa1-xN/GaN multiple quantum well structure grown homoepitaxially by plasma-assisted molecular beam epitaxy on a 4 μm thick (001) IVP-E GaN template. The LPC spectra were taken from 9 to 300 K and compared with photoluminescence (PL) spectra taken over the same temperature range. The undoped MQW structure was grown in the group-III rich regime without growth interruption. The well and barrier width were estimated from X-ray diffraction measurements to be 4 and 16 nanometers (MLs) thick respectively. Rudimentary clastic contacts for the LPC measurements were formed by depositing In into two deeply scribed lines, resulting in electrical contact to both the MQWs and the bulk GaN template. An external electric field of only 3 V/cm is used to collect the photocurrent, which ensures that the electronic properties of the system are essentially unperturbed. Strong excitonic absorption peaks were observed in the LPC measurements up to room temperature in both the bulk GaN layer and the MQW structure indicating that the mobility was not an issue. We find that the PL peak in the MQWs is Stokes-shifted with respect to the PL peak, which we attribute to recombination of excitons from disorder-induced excitonic bound states in the MQWs, resulting primarily from well/barrier interface roughness. A decrease in the temperature dependence of the Stokes shift indicates that above 100 K the excitons involved in the PL are in thermal equilibrium with the lattice prior to recombination. At low temperature the data suggests a non-thermal exciton distribution, which we attribute to exciton trapping in local potential minima. An analysis of the PL integrated intensity versus temperature reveals that the exciton localization energy in the MQWs is 30 ± 5 meV. Theoretical calculations show that this corresponds to fluctuations in the well width of 0.7 ± 0.2 ML. The magnitude of the peak shift due to the excitonic transitions in the MQWs exhibits a non-monotonic variation with temperature, and below approximately 30 K the exciton peak is not discernable. We develop an empirical model to explain this behavior based on the temperature variation of the offset-field mechanism of exciton dissociation and free carrier mobility.

**4:45 PM Y4.11**

**Optical and Nano-Structures of InGaN Films with Average Indium Contents Higher Than 30%**

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Because of the large lattice mismatch between InN and GaN, leading to the low miscibility between them, indium aggregation and phase separation usually occur in InGaN through the process of spinodal decomposition. Such a process results in indium composition fluctuation and the formation of InGaN or InN clusters of quantum dot nature. With such clusters, carriers are localized in potential minima for effective radiative recombination. Typically, the process of spinodal decomposition and hence the evolution of InGaN films as a function of growth parameters is strongly connected with increasing In content. In this paper, we compared the optical and material properties of two MOCVD-grown InGaN thin films with average indium contents about 30% and 40%, respectively, between the 20-nm and post-growth thermally annealed conditions. In the 30% condition, the 30 (40)% sample emits yellow (red) photoluminescence (PL). The major peak of PL spectrum of the 30% sample was shifted from the original yellow band into the blue range upon thermal annealing. Cathodoluminescence spectra of this sample showed that the spectral shift occurred essentially in a shallow layer of the InGaN film. The deeper layers in the asgrown sample contributed to this change because it had been thermally annealed during the growth of the shallow layer. The spectral change was attributed to the reduction of cluster size and possibly the relaxation of quaternized SnSb effect upon thermal annealing. The attribution was supported by the observations in the CL, X-ray diffraction and high-resolution
transmission electron microscopy results. In the 40 % sample, upon thermal annealing the red spectrum was broadened to cover almost the entire visible range. In the other sample, which had been irradiated by an electron beam and not annealed, the green shift is observed to be more prominent. Although the peak intensity is reduced, the spectral width appears to be increased. This behavior suggests that the defect structure is more complex in the irradiated sample. The observed changes in the optical properties during annealing are consistent with the model presented in ref. 4, which predicts a decrease in the density of free carriers upon heating.

Y5.2 Electron Micro-Probe Analysis and cathodoluminescence spectroscopy of Er-doped GaN - Implications on the growth of GaN

S. Dalmasso, B. Willems, G. Brindisi, and M. C. R. de Brabandere

GaN films doped with Er and other rare earth elements (RE) have been investigated using electron micro-probe analysis (EMPA) and cathodoluminescence spectroscopy (CL). The results indicate that the Er doping concentration is higher than expected from the growth conditions, suggesting a possible crystallographic orientation dependence. The CL spectra show a dominant red shift, consistent with the presence of Er ions in the GaN lattice. The study also reveals a significant amount of oxygen-related defects, which may affect the electrical and optical properties of the doped GaN films.
with RE by ion implantation and compare them to results obtained for GaN doped during MBE growth. GaN epilayers grown by MOVCD were investigated in Er, Tm and Eu ions with different concentrations, fluxes and at different implantation temperatures in order to find the optimum implantation conditions. The recovery of the implantation damage was studied using both rapid thermal annealing (RTA) and furnace annealing in nitrogen atmosphere. Rutherford backscattering spectrometry in the channeling mode was used to monitor the evolution of damage introduction and recovery in the GaN substrate and to establish the lattice site location of the RE. The nature of surface contamination was studied using ISS. The structural properties of the samples were analysed by room temperature cathodoluminescence. For optical activation of the implanted samples annealing was performed. We observe RE related emissions in the green, near and blue for Er, Eu and Tm, respectively, and in the infrared for Er and Tm.

Y.5.6 Microstructure and Photoluminescence Investigations of Er Doped GaN Layers grown by MBE, Tomasz Wojciechowskia, Alina Brandc, Hock M. Ng, Jean L. Doussainb and Pierre Rutgersa,1 LERMAF BIE, 2149, CNRS-ENSICAEN, Caen, Normandy, France; 2Laurent Technologies, Murray Hill, New Jersey; 3CIRIL LMB, CNRS-ENSICAEN, Caen, Normandy, France.

For a few years now, it has been possible to dope GaN layers using MBE growth. This aims to use the wide band gap semiconductors as hosts to the rare earth and exploit the sharp emission lines from intra 4f shell transitions. It was shown that the whole visible spectrum can be covered by changing the rare earth or exciting different levels. It is also expected that due to some systems for instance Sn(186)/SiO2, the energy coupling could involve defects. In this work, we carry out TEM and HRTEM analysis on GaN layers grown on sapphire and doped in situ. Investigations are carried out in parallel using photoluminescence and photocathodoluminescence excitation ion experiments in order to determine the mechanisms that govern the energy transfer between the rare earth ion and the host GaN. It has been observed previously that the emission peaks at Er concentrations of about 1% and that it dramatically decreases with Er concentration probably because of compositional quenching. Therefore we study the evolution of the microstructure versus composition and try to explain the quenching effects that can be related to the microstructure. Moreover, it has also been suggested that RE emission in GaN could be related to energy transfer through the mediation of defects. We analyse the atomic structure of the crystallographic defects that are present inside the layers and try to correlate it with the incorporated rare earth atoms.

Y.5.7 Luminescence Properties of Eu ion-implanted GaN, Shin-ichiro Uekan and Iku Takanaka, Department of Electrical and Electronic Engineering, Meiji University, Kawasaki, Kanagawa, Japan.

Since Group III nitrides light device has high luminosity, it is expected as a new white light source replaced with a fluorescent light. Gallium nitride (GaN) is very useful host material because it equips a wide band gap and improve the luminescence properties of rare earth ions. Er ions show low luminescence before impurities. By the transition from the D0 to F1 (J=3/2-1/2), it is expected as a novel which has red light emission in RGB colors. But, luminescence from rare earth ion occurs thermal quenching. Therefore, luminescence is weak and difficult to use at room temperature as a white light source. The wafer used in this work was a 2-3 doped (n=9.8×10^17/cm^3) epitaxial n-GaN layer grown on sapphire substrate. The Eu ion was implanted at an energy of 300keV with a dose of 1×10^16/cm^2 at room temperature. After the ion implantation, these samples were thermally annealed at temperatures ranging from 1000 to 1400°C and at times ranging from 10 to 60 minutes by rapid thermal annealing. The heating and cooling rates were 5°C/A. Before annealing, the apparatus was pumped down to a base pressure of 5.0×10^-10 Torr before an atmosphere gas was fed into the vacuum chamber. The gas used to this experiment was Ar gas at 1 atm. Photoluminescence (PL) spectra and its lifetime were measured at temperature ranging from 15K to 300K with elevated nitrogen and CO laser with a power of 10mW. Signals were dispersed by a 1m focal-distance double-grating monochromator and then detected by a GaAs photomultiplier. Optimal annealing condition was 1200°C, 30 minutes for Er-related luminescence and 200°C, 2 hours for Tm-related luminescence. The Eu with the PL was observed after room temperature. Lifetime is 4.6 ms at 15K and become short as temperature rose. We calculated activation energy (E_a=8.56eV) and studied on thermal quenching process. Its quenching dominated in the low temperature range from 15K to 350 K. It is above threshold for recombination in the transition from the D0 to F2 of Eu. We report systematically on the obtained results.

Y.5.8 Luminescent Holmium Doped Amorphous AIN Thin Films


Holmium doped AIN thin films have been deposited on silicon substrates and optical fibers. The films were characterized by x-ray diffraction, photoluminescence and luminescence characterization. The films are used as waveguides and lasers in optical fiber technology.


Rare earth doped GaN is a promising material with regards to the realization of 3-color integrated optical devices such as diodes. It has been reported that co-doping with O or C enhances the luminescence of Er-doped GaN [1,2]. A possible mechanism that has been suggested in this respect is that these co-dopants may promote the incorporation of Er on substitutional Ga sites. However, the role of co-dopants is currently under discussion and there exist conflicting views whether co-doping is beneficial at all in the case of Er-implanted GaN samples [3]. We report here on emission channeling lattice location studies of as-implanted Er in pure GaN, GaN co-implanted with O and GaN co-implanted with C. The emission channeling technique is based on the fact that charged particles emitted by radioactive probe atoms in a single crystal experience channeling or blocking effects along the major crystal axes and planes. The resulting anisotropic emission yield depends characteristically on the lattice sites occupied by the probe atoms. One of the GaN samples was pre-implanted with 10 net 11 keV using a fluence of 5×10^11/cm^2, a second sample with 5×10^11/cm^2. The energy for the hydrogen was chosen so as to optimize the overlap with the Er atoms. Afterwards radioactive 167Tm (t1/2=9.25 days) was implanted at 60 keV to a dose of 2×10^13/cm^2 into all three samples. The isotope 167Tm decays to the isomer state 167Er (t1/2=2.8 s) of erbium. The conversion electrons emitted in the subsequent decay to the ground state were measured around the [0001], [1-102], [1101] and [2113] directions by means of a two-dimensional position-sensitive detector. Already in the as-implanted state the majority (~75%) of Er was found on substitutional Ga sites in all three samples. The remainder was located on random sites. The root mean square (rms) displacements from the perfect substitutional Ga site were of the order of 0.14 Å in the pure GaN sample, and 0.15 Å in the co-implanted samples. This is larger than the thermal vibrational amplitude of Ga in GaN (0.07 Å), which suggests the Er atoms are slightly displaced or have point defects in their vicinity. Annealing up to 900°C did not significantly improve the substitutional fractions, but decreased the rms displacements down to about 0.11 Å in the pure GaN sample, and to 0.12 Å in the two co-implanted samples. The differences between the three samples are well within the experimental error bars and the Er in the co-implanted samples thus exhibited the same behavior as the Er in pure GaN. Our findings therefore show that co-implantation of Er with O or C into GaN does not significantly affect the incorporation of Er into GaN sites in the case of low-dose ion implantation. [1] J.T. Torvik et al. J. Appl. Phys. 81 (1997) 6345; [2] M. Lippert et al., Nuclei. Sci. Eng. 81 (2001) 121; [3] E. Alves et al., Nuclei. Sci. Eng. 81 (2001) 132.

Y.5.10 Lattice location of Tm, Er and Eu ions in GaN host studied
by X-ray Absorption Fine Structure (EXAFS). Varsholin Kantzkevich 1, Frederic Messina 2, Kevin Peter O’Donnell 1, Takanori Katsumura 3, Y. S. Kim 3, A. Wakahara 4, A. Yashkina 5 and RENIBEL Network 6, 1Department of Physics, Strathclyde University, Glasgow, Scotland, United Kingdom; 2Synchrotron Radiation Center, CCLRC Daresbury Laboratory, Warrington, United Kingdom; 3University of Technology, Tokyo, Japan; 4RENIBEL Network, European Union.

GaN doped with rare-earth (RE) ions is a promising material for light emitting diodes, due to its potential to modify the spectral characteristics of RE ion emission considerably on their distribution over the available lattice and interstitial sites and on the symmetry of the local environment, through the relaxation of selection rules for intra-4f shell transitions [5, 6]. EXAFS measurements can be used to obtain information about local structure in the neighbourhood of an ion targeted by its characteristic X-ray absorption [5]. The main advantages of EXAFS as a structure-determining technique are: it is element-specific and provides information on the local structure around an element which is present in trace concentrations, it is completely non-destructive. Lattice location of RE ions, Eu, Er and Tm, implanted or doped in situ in GaN films has been studied by means of EXAFS measurements at the Daresbury synchrotron.


Y5.11
Enhancement of magnetic properties by co-implantation of Mn and N ions to p-type GaN. Jeong Min Bak 1, Yoon Shon 2, The Won Kang 2 and Jong-Lun Lee 1, 1Materials Science & Engineering, POSTECH, Pohang, Kyungbukkn, South Korea; 2Quantum Functional Semiconductor Research Center, Dongguk University, Seoul, South Korea.

A Mn doped GaN has become one of the most important spintronic materials because its Curie temperature is higher than room temperature according to theoretical calculation of Dietl et al. Recently, room temperature ferromagnetism has been observed in Mn doped GaN. However, it was difficult to obtain a heavy doping of Mn in GaN because of the low solubility limit of Mn in GaN. In this paper, we propose a new method for the enhancement of the Mn solubility in GaN using co-implantation of N and Mn ions into GaN. An undoped GaN layer with a thickness of 1 μm was grown, followed by a growth of a thick p-type GaN doped with Mg. Net hole concentration in the film was determined to be 2.5x1017 cm−3 by Hall measurements. First, the N+ ions were implanted at energy of 35 keV to position the ion peak 80 nm from the surface. The Mg+ ions were then implanted at energy of 180 keV to place its peak range at the same depth as the N+ ions. Furthermore, the N+ and Mg+ ions were simultaneously implanted with doping concentrations of 5x1018 cm−2. Subsequently, annealing at 800 °C for 30 s was performed under flowing N2 gas in a face-to-face condition. For reference, Mn-implanted GaN samples were also prepared. The magnetization data showed that the Curie temperature of the N+ implanted sample was above 300 K. From EXAFS spectra, it was observed that the majority of implanted Mn ions substituted for the Ga sites in GaN. On the other hand, Mn nitrdes such as Mn2N and Mn3N2 were also found and the Curie temperature was low (< 100 K) in the Mn-implanted samples. These results confirm that the ferromagnetism in Mn-doped GaN is derived entirely from the substitution of Mn 2+ ions for Ga sites.

Y5.12
Local structure study of highly Mn doped GaN by fluorescence X-ray absorption. Gema Martinez-Cruz 1, Andrea Simoncini 1, M. Polese 1 and M. Polese 2, 1Micro-Fluorescence/Imaging/Diffraction Group, European Synchrotron Radiation Facility (ESRF), Grenoble, France; 2Walter Schottky Institute, Technical University of Munich, Garching, Munich, Germany.

The atomic configuration and charge states of Mn in GaN were studied by means of extended X-ray absorption fine structure (EXAFS) and magnetic neutron scattering analyses on the micrometer scale. In fluorescence detection mode, the spectra were taken from molecular-beam epitaxy grown GaN:Mn layers deposited on [0001] sapphire substrates with high Mn concentrations, ranging from 1018 up to 1021 cm−3. In addition to the Ga-N type doping, Mn impurities introduce specific magnetic properties, leading to ferromagnetism with an extremely high Curie temperature above 740 K. The systematic behavior of the bond length distortion as Mn content increases in the GaN lattice is reported. The local structure and bonding configurations around the Ga in these films have been analyzed as well. In summary, the obtained local structure has provided direct evidence that the magnetic Mn impurities can indeed substitute for the Ga-host atoms even in highly concentrated samples.

Y5.13
An Optical Spectroscopic Method to Monitor the Formation of the Metallic Secondary Phases in Diluted Magnetic Semiconductor. Sung Soek Ambong Sies 1, T. W. King 1, Y. D. Park 2, G. T. Tickle 3, M. E. Kanatzidis 3, S. J. Pearce 4, H. J. Jeon 5 and T. W. King 6, 1ReCOE & School of Physics, Seoul National University, Seoul, South Korea; 2CSCMR & School of Physics, Seoul National University, Seoul, South Korea; 3Department of Materials and Engineering, University of Florida, Gainesville, Florida; 4Quantum Functional Semiconductor Research Center, Dongguk University, Seoul, South Korea.

Recently, III-V based diluted magnetic semiconductors (DMS) have attracted a lot of attention due to their potential spintronic applications. In spite of development of elaborate growth techniques, it is still difficult to realize formation of secondary phases due to the solubility limit. Especially, formation of some inter-metallic compounds, such as MnAs, Mn3N2, and GaMn, should be carefully monitored, since they are known to form ferromagnetic high Curie temperature phases. So far, standard X-ray diffraction and transmission electron microscopy measurements have been widely used, but the possible formation of the secondary phases and their roles in the observed ferromagnetic properties remain to be controversial. Therefore, it is a highly desirable to develop noble experimental techniques to check the formation of the secondary phases. We found that optical spectroscopy techniques can provide a nondestructive method to monitor the formation of such metallic secondary phases by observing a resonant absorption, called ‘r plasmon resonance’, in transmission spectra. For example, we will show the optical spectroscopic evidence on the formation of Mn3N inter-metallic particles in GaN:Mn, by observing the 1eV resonant absorption and comparing its temperature dependence with predictions of the Maxwell-Garnett theory. Moreover, our optical spectroscopic techniques can provide quantitative information, such as the volume fraction of Mn3N inter-metallic particles. In this presentation, we will show how the optical spectroscopic technique allows us to monitor the formation of the metallic secondary phases in various DMS samples, such as GaN:Mn, GaAs:Mn, and InAs:Mn. The optical spectroscopic signatures of possible metallic secondary phases in each DMS and analysis method will be also discussed. References [1] See et al., Appl. Phys. Lett., 82, 4749 (2003).

Y5.14
Resonant Magnetopolaron Effect on Shallow Donors in GaN. Andrey Stefan Wysmolek 1, R. Stepieniewski 1, M. Polese 2, B. Cwikel 3, K. P. Korona 4, J. M. Barczynski 3, D. C. Lock 5, S. S. Park 6 and K. Y. Lee 7, 1Institute of Experimental Physics, Warsaw University, Warsaw, Poland; 2Grenoble High Magnetic Field Laboratory, Grenoble, France; 4Department of Electrical Engineering, Wright State University, Dayton, Ohio; 5Samsung Advance Institute of Technology, Suwon, South Korea.

The interaction of longitudinal (LO) phonon with highly excited shallow donor states in GaN, observed using magneto-spectroscopy of neutral donor bound excitons (DOX) in magnetic fields up to 28 T, is reported. The magneto-photoluminescence experiments have been performed on a thick freestanding GaN. Photoluminescence spectrum of this material shows pronounced emission due to silicon and oxygen donor bound excitons. Beside the principal recombination transition of DOX in which donors are left in one of the excited states with n = 2 (2s, 2p, 2p, and 2p+), as well as excitations to several higher (n > 2) donor states [1]. The intensities of TES related to the states with high n-index decrease with increasing of the magnetic field strength. However, when the high n-index states are tuned into resonance with LO-phonon replica of the principal DOX transition, their intensities are strongly enhanced. The avoided crossing between LO-phonon and several donor states is observed. The strongest effects are observed for a series of n = 6, 8, 10, 12, 14, 16, 18, which, in general, are characterized by n=1 and n=2 quantum numbers. The characteristic property of these states is that their wavefunctions are extended along the magnetic field direction. These results are discussed in terms of electron-phonon interaction and provide information about the magnitude of the resonant interaction of LO-phonons with impurity-bound electrons in GaN. [1] A. Wysmolek, K. P. Korona, R. Stepieniewski, J. M. Barczynski, M. Polese, M. Potemski, R. I. Jones, D. C. Lock, J. Kuhl, S. S. Park, and S. K. Lee.
Y.5.15 Hydrogen-related Local Vibrational Modes in GaN:Mg Grown by Molecular Beam Epitaxy. David Pastor1, Ramon Casado2, Luis Artés3, Fernando Narango4 and Enrique Calella2; 1Instituto de Microelectrónica de Sevilla-CSIC, 2Departamento de Ingeniería Electrónica, ETSI Telecomunicación, Universidad Politécnica, Madrid, Spain.

Despite the achievement of effective p-type doping of GaN using Mg as a dopant, basic understanding of p-type doping still remains an issue. It has been recognized that hydrogen plays an important role in p-type doping of GaN, strongly passivating the acceptor states of MOCVD-grown GaN and making post-growth annealing treatments necessary to obtain p-type conductivity. Contrarily, GaN:Mg samples grown by MBE usually exhibit native p-type character in the as-grown state. We report a Raman scattering study of Leigh Reconstruction (LR) and Mg-doped GaN (LVMs) and GaN:Mg grown by MBE. The samples were Mg-doped GaN films of 1 μm thickness grown on Si(111) substrates at TMBE = 450 °C. The Raman experiments were performed using a Raman microscope with the 514.5 nm excitation wavelength and typical spot size of 1 μm. The spectra were acquired in the x(yyy) in-plane configuration to maximize the scattering volume. In the region of the acoustic and optical modes of GaN, we clearly observed two distinct peaks at 320 and 656 cm⁻¹, which correspond to local Mg modes with Aυ symmetry. These LVM peaks, which unambiguously show the presence of Mg dopants in substitutional Ga positions, were observed in MOCVD samples only after thermal annealing. Additionally, we observed four Raman peaks in the spectral region around 2200 cm⁻¹, where LVM associated with Mg-H complexes and H-decorated nitrogen vacancies occur, suggesting that H passivation may also take place in GaN:Mg samples grown by MBE. Contrary to the case of MOCVD samples, we did not detect any Raman peak at about 321 cm⁻¹, which indicates that the role of H-related states for MBE growth is different.

The different behavior of H in hydrogenated GaN:Mg samples grown by MBE and MOCVD correlates with the different electrical behavior that is usually exhibited by samples grown using these two techniques.

Y.5.16 Non-Equilibrium Acceptor Concentration in GaN:Mg Grown by Metallorganic Chemical Vapor Deposition. Yinyin Gong1, Y Gu1, Igor L Kukusovskiy1, GP Neemark1, J Li2, J Y Lin3 and H X Jiang4; 1Department of Applied Physics and Applied Mathematics, Columbia University, New York, New York; 2Department of Physics, Kansas State University, Manhattan, Kansas.

GaN has been of great interest for various applications. To achieve optimal device operation, good bipolar doping is required. GaN:Mg with a hole concentration of 10¹⁷ cm⁻³ has been achieved for (a review, see e.g. [1]). Such good p-doping is obtained either by post-growth annealing of material grown by metalorganic chemical vapor deposition (MOCVD), where such annealing removes compensating hydrogen, or by hydrogen-containing Mg dopant. Both processes are expected to result in non-equilibrium dopant concentrations [2, 3]. Here, we present experimental results that prove non-equilibrium concentrations for the MOCVD case. Our samples are cut from a single wafer of GaN:Mg grown by MOCVD on sapphire and activated by rapid thermal annealing (RTA) at 950 °C for 8 sec. We then further annealed several of these pieces at various temperatures in nitrogen ambient for over 12 hours. Temperature-dependent Hall-effect measurements showed that hole concentrations decreased by an order of magnitude or more in samples annealed at high temperatures (>850 °C) compared with the original RTA activated sample, while the acceptor activation energy remains the same for all pieces. This behavior is explained by Mg concentrations in excess of the equilibrium solubility limit. Thus, at high enough temperatures, Mg, in the absence of hydrogen, diffuses either to form electrically inactive precipitates or is eliminated. Furthermore, we shall show that photoluminescence measurements are consistent with the Hall-effect measurements.

Y.5.17 Effect of Impurities on Raman and Photoluminescence Spectra of AlN Bulk Crystals. Andrei Sarun1, Sreekumar Rajanagam1, Martin Kaball1, Maria Garro2, Oscar Sanchez2, Ana Gross2, Andrea Cantore3, Daniel Ogiso4, Bei Liu5, Dejin Zhang4 and Juan H. E. Everts, 1Department of Physics, University of Bristol, Bristol, United Kingdom; 2Instituto de Ciencia de Materiales de Aragón, Universidad de Zaragoza, Zaragoza, Spain; 3Dpto. de Física, Centro de Investigación y de Estudios Avanzados del Instituto Politécnico Nacional, Mexico, Mexico; 4Department of Chemical Engineering, Kansas State University, Manhattan, Kansas.

AlN has attracted great attention for its use as a wide bandgap high thermal conductivity substrate for electronic and optoelectronic devices. However, its properties are highly affected by incorporation of impurities during growth, for instance AlN has a large affinity to oxygen. Raman and photoluminescence (PL) spectroscopy were applied to explore the nature of impurities in AlN by optical means, in particular of oxygen. Bulk AlN crystals grown under high pressure sublimation method were studied. Composition analysis of the wafers was obtained by EDS, Leco combustion and infrared absorption spectroscopy. The levels of oxygen, carbon, silicon and magnesium impurities were derived from these analyses. Micro-Raman spectra of the bulk AlN samples were measured in different polarizations and at different excitation wavelengths. The presence of vibrational modes at 385 cm⁻¹ and 930-950 cm⁻¹ was detected in addition to the usual Raman modes of bulk AlN. The 385 cm⁻¹ mode is assigned to oxygen in an apical vibrational mode (LVM) in AlN, Al-O complex. PL measurements were performed with sub-bandgap light excitations of 4.5 eV and 3.72 eV. A correlation between the observed 385 cm⁻¹ mode and an oxygen related luminescence band in PL spectra at 3.3 eV was found. Theoretical calculations were performed to understand the origin of LVMs in AlN and reasonable agreement to the experimental value for the oxygen LVM was achieved.

Y.5.18 Surface Potential Measurements of Doping and Defects of p-GaN. Maria Losurdo1, Mariiha Michael Giangregorio1, Giovanni Bruno1, April Sam Brown2, William Alen Doucette3, Gan Nonkocon3 and Thomas Myers3; 1Plasma Chemistry Center, IMP-CNRS, Bari, Italy; 2Electrical and Computer Engineering, Duke University, Durham, North Carolina; 3School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, Georgia.

Effective p-type doping in GaN is still a crucial issue for the realization of efficient optical and electronic devices. The most investigated n-dopants of Mg and Be suffer from receptor passivation through hydrogen complexes. In this study, we use non-destructive optical and electrical probes such as spectroscopic ellipsometry and Kelvin probe force microscopy (KPFM) in conjunction with non-contact atomic force microscopy (AFM) for investigating the interaction of Mg- and Be-dopants with atomic hydrogen and for characterizing passivation of defects, such as, dislocations, microcracks and inversion domains with atomic hydrogen. GaN epitaxial films grown by metalorganic chemical vapor deposition (MOCVD) and molecular beam epitaxy (MBE) doped with both Be and Mg at a doping level in the range from 10¹⁷ cm⁻³ to 10²¹ cm⁻³ are exposed to an atomic hydrogen flux produced by a r.f. (13.5MHz) remote plasma source. The reactivity towards atomic hydrogen including bulk hydrogen diffusion, defect (dislocations) passivation and p-dopant deactivation is monitored in real time by spectroscopic ellipsometry that monitors variation of the GaN dielectric function upon atomic hydrogen exposure. Through the analysis of the broadening, energy-shift and amplitude of the GaN exciton transition at 3.4 eV in the ellipsometric spectra, the effect of atomic hydrogen on p-dopant deactivation is inferred. The ellipsometry data are corroborated by surface potential variations. Surface potential measurements reveal a decrease in surface potential directly correlated with the degree of deactivation of the Mg-MgOdoped sample. Effective p-type doping of Mg on the GaN surface potential. An increase in donor density in the GaN by either n-doping or hydrogen-related deactivation of p-dopant result in reduced SKP signal because of the shift of the Fermi level towards the conduction band. The effect of surface temperature and p-dopant concentration on the MgH and Be-H interaction is investigated. Furthermore, direct measurements of potential variations around dislocations, microcracks and inversion domains are detected to reveal the nature of the above effect charge as well as their spatial extent and modifications by atomic hydrogen treatments.
Y 5.20

Formation and Dissociation of Hydrogen-related Defect Centers in Mg-doped GaN. [111]

The low activation rate of Mg (roughly 1%) in this work, we show the improvement of activation rate and ohmic contact characteristics by rapid thermal annealing (RTA) using a high-temperature anneal on Mg-doped GaN layer. Electrical characteristics of Mg-doped p-GaN grown on sapphire substrates by metal organic chemical vapour deposition (MOCVD) and activation by RTA using Na and Au catalyst layers were investigated using Hall measurements and current-voltage (I-V) characteristics. We also fabricated and compared the LED with normal temperature used commonly in our fabrication process (800 °C) and with low temperature activation using catalyst layer. The p-GaN layer was grown on sapphire substrates by metal organic chemical vapour deposition (MOCVD) and activation by RTA using Na and Au catalyst layers were investigated using Hall measurements and current-voltage (I-V) characteristics. It was revealed that Ni and Au layers on p-GaN enhance activation of the acceptor. This enhancement can be attributed to the catalytic effect for the hydrogen desorption and ionization energies of Mg acceptors in p-GaN layer activated with Na. Au shows better catalytic effect in p-GaN layer and the electrical and optical properties of InGaN/GaN blue LEDs due to improved ohmic characteristics by increase of Mg activation rate and reduction of degradation of InGaN/GaN quantum well by low temperature activation of Mg using catalyst layer in LED structures.

Y 5.22

TEM Investigation of Defect Reduction and Etch Pit Formation in GaN. Angelika Vennemann, Jinse Densmire, Claudin Reder, Roland Kroeger, Tim Boettcher, Detlef Hemmel and Peter Rydle; Institute of Solid State Physics, University of Bremen, Bremen, Germany.

The reduction of the threading dislocation (TD) density in GaN grown by metal organic vapor phase epitaxy (MOVPE) is of major importance in order to improve electronic devices. With the investigated SiN, micromasking the dislocation density can be reduced by more than an order of magnitude, as shown by plan view transmission electron microscopy (TEM). The reduction of TDs in GaN grown on 4H-SiC and 6H-SiC is due to bending of the TDs into the (0001) plane, such that they form dislocation loops if they meet dislocations with opposite Burgers vectors. Additionally, the achievable reduction of the dislocation density is limited by the probability that appropriate dislocations meet. In order to gain easier access to the dislocation structure, the GaN samples of this study were chemically wet etched with an H2SO4 : H2PO4 acid for varying times. The atomic force microscopy (AFM) and TEM investigations showed different types of etch pits. After brief etching, pure edge dislocations and several dislocations of pure screw or mixed character showed no clearly distinguishable etch pits, whereas several dislocations with screw component showed large etch pits with diameters of about 0.5 μm. These are assumed to be etch pits associated with open core dislocations or nanovoids. In samples containing a SiN, micromask, preferential bending of edge type threading dislocations at the SiN, interlayer was observed, which is in contrast to the results found for GaN grown on silicon [Contreras et al., Appl. Phys. Lett. 81 (2002) 472]. This might be attributed to the different strain state of GaN grown on silicon or sapphire, as revealed by temperature dependent X-ray diffraction (XRD).

Y 5.23


Recent increased interest in GaN/AlGaN quantum wells (QWs) is primarily governed by possibilities of the fabrication of new opto-electronic devices such as optical modulators, switches, etc. The mobility and distribution of the carriers in these structures are strongly dependent on the smoothness of the quantum wells as well as on the sharpness of their interfaces. Reliable measurement of the uniformity of these QWs is needed. For characterization of these GaN/AlGaN QWs, when the width of the wells is as small as 10−15 A, scanning transmission electron microscopy with ~2 Å probe is ideal for these type of measurements. The samples of wurtzite GaN/AlGaN QWs studied here were grown in an MBE system and consist of 20 GaN/AlGaN QWs with initially estimated 60 Å AIBAR layers and 120 Å GaN wells. Composition sensitive and electron energy-loss spectroscopy (EELS) were used to determine long-range uniformities of GaN quantum wells and the sharpness of their interfaces as grown in an AIN matrix by molecular beam epitaxy. Low magnification annular dark field images reveal waviness along the growth plane with a period of ~50 Å and a height ~20 Å in one sample and significant changes of the long-range uniformity in the other. The measurements of the changes in energy-loss spectra of the AI L (2p) edge, Ga L2.3-edge and Mg K-edge indicate that the interfaces between the QWs and the barriers are in most cases almost atomically sharp while in some cases they are not. For a better understanding of these results, the authors present evidence of the interaction of an incident electron beam with specimen were also performed to calculate beam spreading inside the sample.

Y 5.24

TEM Analysis of Polarity of GaN Grown by MOCVD on Sapph.
GaAs(111)A and (111)B. Noriyuki Kuswara 1, Y. Ohashi 2, Nao Murakami 1, Y. Kangawa 1, Y. Kimura 2 and A. Koukitu 1*


Gallium arsenide (GaAs) (111) is a very attractive substrate for growing a free-standing GaN. However, crystals of GaAs and GaN do not have inversion symmetry either, and thus they have a polarity along (111) and (001), respectively. Since the growth process of GaN depends strongly upon the surface structure, the polarity along the growth direction is an important factor of GaN crystal quality. In this work, GaN layers were grown by the metalorganic hydride vapor phase epitaxy (MOHVEP) method on both sides of GaAs(111)A and (111)B. The growth temperature was maintained at $500 \pm 5^\circ C$. A buffer layer of about $100 \text{nm}$ thick and $550 \pm 50^\circ C$ for a GaN layer about $8 \mu m$. TEM observation was performed to analyze the microstructure of the GaN layers. The polarity of GaN was examined by the convergent beam electron diffraction (CBED) technique. Good epitaxial growth was found to grow in the zincblende structure with stacking faults. The GaN layer grown at $850^\circ C$ is made of columnar wurtzite crystals containing many stacking faults parallel to (001). The wurtzite GaN layers were confirmed to have Ga-polarity along the growth direction irrespective of the polarity of the substrate plane. The GaN layer grown at $950^\circ C$ is made of zincblende structure in the lower part and wurtzite structure in the upper. The wurtzite part contains few stacking faults and has a Ga-polarity along the growth direction. The zincblende part was revealed to have a polarity corresponding to the one of the substrate plane. The results implied that at high temperature the wurtzite crystal grows continuously on the zincblende GaN. The change in stacking order and the inversion of polarity are also discussed.

Y. S. Armitage, S. Qiang, and E. R. Weber 1, 3, 5, 6, 7, 8, 9, 10

1. Semiconductor Research Center, Wright State University, Dayton, Ohio; 2. Department of Materials Science and Engineering, University of California, Berkeley, California; 3. Lawrence Berkeley National Laboratory, Berkeley, California.

Understanding the properties of carbon-related defects in GaN is necessary to evaluate the suitability of the material for next-generation semiconductor devices. In this study, GaN layers were grown on semi-insulating Si MOVCD GaN templates by plasma-assisted MBE in growth conditions using CCl$_4$ as a doping source. Three samples, including a Si MOVCD-GaN sample, were characterized by using SIMS, resistivity, and thermally stimulated current (TSC) spectroscopy. As [C] increases from $3 \times 10^{18}$ to $3 \times 10^{19}$ cm$^{-3}$, the MOVCD GaN to $2 \times 10^{18}$ and $2 \times 10^{19}$ cm$^{-3}$ in the lightly and heavily C-doped MBE GaN samples, respectively, reduces from about $1 \times 10^{14}$ to $1 \times 10^{16}$ and $1 \times 10^{11}$ cm$^{-3}$. These defects disappear or dark current decreases from 0.70 eV to 0.32 and 0.33 eV. In the SL-MOCVD sample, we find at least six TSC traps, B$_{5}$ (0.51 eV), C$_{5}$ (0.44 eV), C$_{6}$ (0.82 eV), D$_{5}$ (0.23 eV), E$_{5}$ (0.16 eV), and F$_{5}$ (0.16 eV), which are very similar to electron traps found in $n$-type GaN films by using deep level transient spectroscopy. However, in the MBE-GaN sample with the lowest value of [C], the only observed traps are B$_{5}$ and E$_{5}$ and the relative trap density of trap E over trap B is significantly reduced. In the MBE-GaN sample with the highest value of [C], both traps E and B are suppressed, and instead, trap B$_{5}$ is prominent. Based on the results of deep centers induced by electron irradiation and etching, we believe that C$_{5}$, P, and B$_{5}$ are related to V$_{A}$, and B$_{5}$ might be related to V$_{A}$. Incorporation of [C] in GaN introduces C$_{5}$ acceptors, resulting in compensation and formation of SL-GaN; however, more [C] causes suppression of V$_{A}$. As even more [C] is incorporated, the concentration of C$_{5}$ is saturated and the concentration of C$_{5}$ is significantly reduced by C-doping actually decreases. This is attributed to incorporation of an increasingly large fraction of total carbon in the form of C$_{5}$, or a related complex. The heavily C-doped GaN sample also exhibits very strong photocurrent and persistent photoconductivity at 83 K. These phenomena can perhaps be related to the presence of C$_{5}$D$_{5}$ donors.
transmission electron microscopy. Cross-section images reveal crack formation. Cracks start in GaN approximately 1.6 mm from the buffer layer and propagate through the epilayer. Threading dislocations, with the density of $\sim 4 \times 10^{10} \text{ cm}^{-2}$, and stacking faults (SFs) are also observed. These dislocations are mainly partial dislocations which terminate SFs. The density of SFs is $\sim 1 \times 10^{10} \text{ cm}^{-2}$, as derived from plan-view transmission electron microscopy (TEM). A number of SFs are Type 1, low-energy planar defects. In some cases SFs with higher formation energy are also observed. Microstructure and defect formation mechanism will be discussed in conjunction with epitaxial growth process.

Y.5.29


C-plane sapphire often remains the substrate of choice for epitaxial growth of III-nitrides films. However, due to the large lattice and thermal expansion coefficient mismatch, high densities of structural defects are formed inside such nitride films. Different types of structural defects (threading dislocations, dislocation loops, basal stacking faults, monopoles, and inversion domains) in GaN grown on sapphire have been addressed by numerous studies. On the other hand, much less has been done in case of AIN films grown on sapphire despite the growing interest in their potential applications in high power and high temperature devices. Here in this paper we will report on structural study of various types of internal defects formed inside AIN films grown on nitrided c-plane sapphire substrates. It will be shown that these defects correlate with small islands on the surface that are observed by atomic force microscopy (AFM). Moreover, with use of different techniques of transmission electron microscopy (TEM) we identified these defects as inversion domains, e.g. V-shape columns of AIN grown with opposite polarity. Strong experimental evidence will be provided to support this identification. The absolute polarity of these inversion domains will be also analyzed and the model of inversion domain boundaries will be discussed.

Y.5.30


Recently, high quality non-polar Al-Plane GaN films have been successfully grown on R-Plane sapphire substrates. Significant quality improvements have resulted from the suppression of threading dislocation, dislocation network, and smooth growth surfaces. While it is expected that TEM defects analysis on conventionally grown epitaxially grown GaN on polar substrates is widely carried out, to our knowledge this is the first time that TEM defects were measured for the Al-Plane GaN epitaxial samples. For the ELOG samples, it remains the same for the window area but reduces dramatically for the wing area material. For the fully coated Al-Plane GaN on R-Plane, the dislocation density was reduced to below our TEM measurement limit. AFM images of the sample surface, which reveal dislocations, were about 10/5 μm². Stacking faults were found to be present both in the ELOG and the R-Plane Al-Plane GaN films. We present the details of the ELOG/R-Plane growth procedures and a model that explains the mechanism of stacking fault formation in them.

Y.5.31


A defective zone in the HVPE-deposited GaN was investigated by transmission electron microscopy (TEM) of cross-section and plan-view TEM samples. It was shown that the defective zone is formed during the process of nucleation, coalescence and overgrowth of three-dimensional islands. The islands differ by a non-equivalent translation with respect to the reference (substrate) lattice, and therefore their coalescence results in formation of translational (stacking fault-type) boundaries. For the processing conditions used in the HVPE deposition, it appears that the islands adopt a shape of [113]-faceted truncated pyramids. Continued coalescence and overgrowth of the crystallographically non-equivalent grains result in a substructure of connected (0001) and (1120) stacking faults, as well as in threading dislocations. A density of threading dislocations of GaN grown by HVPE is shown to increase with the thickness of the defective zone. The extend of the defective zone depends on the nucleation frequency and anisotropic growth rate of different crystallographic facets.

Y.5.32


For the last decade, GaN and related compounds have been of great interest due to the development of applications such as high-brightness light-emitting diodes and laser diodes operating in the blue/green to ultraviolet range. Significant progress has been achieved in the growth process of GaN. Most of the work done on GaN has taken into account layers grown on the (0001) sapphire plane. However, one would expect the growth on the [1120] plane to lead to different structural defects. As has been shown, in one direction, the mismatch is rather small. In this work, we have carried out structural analysis of monolayer layers grown at temperatures ranging from 600 C to 1100 C. In addition, we have investigated layers nucleated at the temperature of 1028 C by varying the pressure and we tried to monitor the growth mode. It is shown that structural parameters, such as the orientation relationship, the layer morphology and the nucleation mechanism critically depend on the growth temperature. At the lowest temperatures, the growth is completely three-dimensional, with a mixture of the two traditional orientation relationships, and with a small value of film thickness necessary to achieve coalescence. The A [11-20]GaN orientation relationship predominates and the layer thickness tends to slightly decrease. The A orientation relationship is never perfect anywhere, as well as the associated defects, may be directly controlled by introducing growth conditions. Because the growth was directly deposited on the sapphire substrate, we have also investigated this phenomenon by using CBE substrates.

Y.5.33

the devices, degradation of the microstructure due to the impurity compromises the effect as the doping level increases to 1020 cm$^{-3}$.

Y.5.34 Structural Units and Energy of Grain Boundaries in GaN.
Gerard Novat, Peter Ruetschn and Jin Chen; ERMAT,
ENSICAEN, Caen, France.

GaN layers grown by MBE or MOCVD contains a high density of threading dislocations. They may form low-angle and high-angle grain boundaries. The structural dislocation and grain boundary structure of the 1/n<1120> edge dislocation was previously investigated by HREM and atomic calculation. This dislocation may present three different cores corresponding to the 4, 57 or 87 atom ring. The tilt grain boundaries around <001> B are constructed with the same dislocations and these three cores were identified by HREM in these grain boundaries. The potential energy of these grain boundaries in the range 48-60 degrees was calculated by using the Willinger potential after modification to take into account the Ga-N bond length in the core of the defects. In this work, the energy of other grain boundaries corresponding to the diagonal of the unit cell of the coincidence site lattice have been calculated. The comparison with the first results corresponding to the edges of the unit cell shows that the energy depends on the type of structural units used to construct the grain boundary. The 57 atom ring leads to energy values lower than the 57-57 atom ring. This difference may be explained by considering the Burgers vector associated with the structural units. For the 57 atom ring, the Burgers vector is normal to the grain boundary plane whereas the 57-57 atom ring is characterized by 60 degree Burgers vector and lead to higher energy values in this case. In addition, supplementary stress is expected to be origin of the largest energy values calculated for the configurations involving the 57-57 atom ring.

Y.5.35 Phase Separation and Atomic Ordering in InGaN Mixed Layers: Munu Rho, Duwoo Kim, Yongjun Wang and Subhash Mahajan; Department of Materials and Materials Engineering, Arizona State University, Tempe, Arizona.

Atomic ordering has been mainly observed in InGaN layers grown by MBE but has been reported in InGaN grown by MOCVD. Phase separation has been observed to occur in alloys with higher In contents. Phase separation and ordering affect properties such as the mobility, band-gap and luminescence and therefore are of significant interest. The mechanism responsible for the evolution of the ordered structures and the relationship with phase separation are not well understood in InGaN layers. Using MOCVD, thin GaN nucleation layers were deposited on (0001) sapphire substrates at low temperature followed by annealing. The annealing resulted in a change in the microstructure to give larger islands bounded by {10-11} facets. In one sample a thick GaN buffer layer was then deposited, which planarized the surface, and this was followed in all samples by growth of InGaN layers. Phase separation has been observed to occur in alloys with higher In contents. Phase separation and ordering affect properties such as the mobility, band-gap and luminescence and therefore are of significant interest. The mechanism responsible for the evolution of the ordered structures and the relationship with phase separation are not well understood in InGaN layers. Using MOCVD, thin GaN nucleation layers were deposited on (0001) sapphire substrates at low temperature followed by annealing. The annealing resulted in a change in the microstructure to give larger islands bounded by {10-11} facets. In one sample a thick GaN buffer layer was then deposited, which planarized the surface, and this was followed in all samples by growth of InGaN layers. Phase separation has been observed to occur in alloys with higher In contents. The [10-11] spot is a systematic extinction in the [10-10] diffraction pattern. However, this and equivalent spots in the 0001 diffraction pattern were present when InGaN was deposited on unannealed nucleation layers but not when deposited on GaN buffer layers. Therefore, the surface faceting is probably responsible for formation of the ordered structure. The superlattice spots were present only in thicker InGaN films, suggesting that the structure is only weakly ordered. Phase separation was detected in all samples in this series. Spots in the diffraction patterns exhibit satellites oriented in <1-201> directions relative to the fundamental reflections. The wavelengths of these composition modulations were calculated to be 8-11nm. The support of this work by NSF is gratefully acknowledged.

Y.5.36 Analysis of InGaN-GaN Quantum Well Chemistry and Interfacial Structure. J. S. Burns, D. M. Graham, P. Dawson, and C. J. Humphreys; Department of Materials Science and Metallurgy, University of Cambridge, Cambridge, United Kingdom; Department of Physics, UMIST, Manchester, United Kingdom.

In the past, the localization of excitons in InGaN/GaN quantum wells has been attributed both to indium composition fluctuations (indium "clustering") and to reduced thicknesses and widths of the wells. We have studied a range of InGaN quantum well samples using high resolution transmission electron microscopy (HRTEM), high angle annular dark field-scanning TEM (HAADF-STEM), including results from an aberration corrected STEM, high resolution X-ray diffraction (HRXRD) and X-ray reflectivity (XRR). The material was grown MOVPE using a close coupled showerhead reactor with InGaN growth temperatures between 700 °C and 750 °C. Detailed photoluminescence (PL) measurements indicate that localization of excitons in a length scale of the order of a few nanometers is present in these samples, with a high PL internal quantum efficiency (for example of 43% for a multiple quantum well structure with room temperature peak emission of 486 nm). Our evidence suggests that these InGaN layers do in fact exhibit the kind of ground-state clustering which other workers have reported for their material. However, from multiple characterization techniques we detected clear evidence for symmetry in the widths of the interfaces of the quantum wells. While the GaN:In interface seems to be fairly abrupt, the InGaN:Ga upper interface is more gradual. This is indicative of the presence of a compositional wave or interface roughening during the growth. The InGaN layer growth or the indium incorporation into the GaN barrier once the indium source has been switched off. In contrast to the prevailing opinion in the literature, it seems that excitation in these structures is not due to strong variations in the alloy composition.

Y.5.37 Deep Defects In Fe-Doped GaN Layer Analysed By Electric And Photoelectric Spectroscopic Methods. Hartmut Witte, Kevin Flasche, Andre Kirsch, Armin Dycher, Albrecht Christian; Institute of Experimental Physics, University of Magdeburg, Magdeburg, Germany.

Insulating GaN layers are essential for applications in high-frequency and high-voltage devices. Iron doping of the GaN layers is a useful approach to produce the semi-insulating properties, however, this changes the concentration of deep defect levels and introduces additional impurities. In particular, the detailed knowledge of the complex compensation mechanisms in iron-doped GaN layers is sparse up to now. We have analyzed defects in Fe-doped GaN layers grown by metal-organic vapor phase epitaxy on sapphire as well as on Si substrates using temperature dependent Hall effect (TE), photoluminescence (PL) and absorption measurements as well as changes in the defect spectrum determined by DLTS and TSC. With increasing Fe-doping level the resistivity increases. A p-type conductivity is found for Fe content and a dominant acceptor with an activation energy of about 450-460 meV is found in TDH. In the PC and TSC spectra deep defect-to-band transitions and defect emissions at energies between 0.8 eV and 0.9 eV were observed which are related to Fe defect states. In the n-type Fe-doped samples other defects with activation energies of 350 meV and 600 meV were detected by TSC and TSC, whereas shallower defect states were found to be suppressed. Quenching effects caused by an additional sub-band gap illumination diminishes with increasing Fe incorporation. Based on these results, the influence of the Fe doping on the compensation mechanism will be discussed in detail.

Y.5.38 Identification of Carbon-related Bandgap States in GaN Grown by MOCVD. Andrew Michael Armstrong, Aaron R. Archard, Brendan Morris, James S. Speck, Umesh K. Mishra, Steven P. DenBaars, and Steven A. Ringel; Electrical Engineering, The Ohio State University, Columbus, Ohio; Materials Department and Computer Engineering, University of California, Santa Barbara, Santa Barbara, Ohio.

Carbon doping of GaN is of great interest in part because it has been shown to result in semi-insulating behavior. However, determination of the bandgap states and hence the exact mechanism responsible for the SI behavior is, to date, unresolved. An important step in this investigation is to determine the contribution of C dopants to the total bandgap states in n-type carbon doped GaN. The results show the presence of a shallow state at $E_C + 3.38$ eV ($E_V - 0.16$ eV) for the LP samples with a minimum concentration of $3.6 \times 10^{18}$ cm$^{-3}$, that efficiently compensates Si donors for the $p$-doped sample and results in semi-insulating behavior for the $n$-type LP sample. In contrast, this state is not observed for the $n$-type GaN material, which incorporates a factor of 2 times less C, and instead only the deep level acceptor state at $E_C + 3.22$ eV is observed. Additionally, a state at $E_C + 1.35$ eV, near the theoretically expected C split-intovalent level in n-type GaN, is observed to increase significantly in concentration with increasing C concentration. The origin of this state and its role in the electronic properties of GaN are under further investigation.
both LP and AP MOCVD growth will be discussed.

Y5.39
Band Bending near the Surface in GaN as Detected by a Charge Sensitive Probe. Shiori Sato, Kazuaki Tsuchiya, Takashi Hara, Toru Sugahara, Yutaka Ohishi, Department of Electrical and Electronic Engineering, Tohoku University, Sendai, Japan.

GaN-based optical and electronic devices have progressed rapidly in recent years. However only a little attention has been given to the effect of the surface on the properties of GaN and related devices. It is well known that the surface of undoped GaN, both nominally clean and purposely cleaved, exhibited an upward band bending of the order of 1 eV [1]. It is also known that a thin oxide layer, as well as adsorbed oxygen atoms, covers the GaN surface. We measured the absolute value of surface band bending with Dimension 3100 atomic force microscope in the surface potential mode. Planar samples were cleaved in a low pressure argon environment. The surface potential measurement on our GaN samples showed an upward band bending of about 0.7 eV. The samples studied in detail for one week showed an increase in band bending by up to 0.1 eV. The effect of UV exposure (with a pulse nitrogen laser) on band bending was studied in detail for selected samples. Typically, the surface barrier decreased by about 0.2 eV and the decrease saturated at excitation intensities above 10^3 photons per pulse. Very slowly (by a logarithmic law) the barrier got restored in dark at room temperature. These and other similar phenomena are preliminarily explained by the combination of photo-induced desorption of oxygen from the surface and thermodynamically driven free electrons from the bulk to the surface states. [1] V. M. Bermudes, J. Appl. Phys. 80, 1190 (1996).

Y5.40

We clearly show the difference in reciprocal space mapping (RSM) of x-ray diffraction (XRD) intensity of GaN-based laser diodes (LDs) on various GaN templates such as GaN/AlN/GaN and GaN substrates. The tilt distribution, derived from the RSM of XRD intensity of the LDs grown on GaN substrates, is smaller than that of the LDs grown on GaN/AlN substrates. This result indicates GaN substrates are favorable to realize the superior LD characteristics. The LDs have the same structure of separated confinement heterostructure except for substrates: GaN substrate and GaN/AlN substrate. The RSM recorded x-ray intensity using the asymmetric (161) reflection from the LD structures grown on GaN substrate and GaN/AlN substrate. The incident beam was the x-ray with Cu Kα radiation (λ = 1.54056 nm) through the asymmetric four-crystal Ge (200) monochromator. AlGaN and InGaN were fully strained, from the RSM of the LDs both on GaN/AlN substrate and GaN/AlN substrate. However, the distribution of XRD intensity in these maps was quite different. The full width at half maximum in x-ray from the LDs grown on GaN substrate was reduced as small as 0.05° compared with that of the LDs grown on GaN/AlN substrate. Therefore, we found that the tilt distribution of the LDs on GaN substrate, corresponding to the broadening of x-ray scan, was smaller than that on GaN/AlN substrate. We will demonstrate the device characteristics of these LDs at the meeting.

Y5.41
Thermal Stability of Iridium Schottky Contacts on n-AlGaN. Alain Kuliak, Deepak Solanki, Vijay Kumar, Seiyon Kim, Gabriel Guevara and Tammi Adesida, Department of Electrical and Computer Engineering, University of Illinois at Urbana-Champaign, Urbana, Illinois.

Group III-nitride semiconductors offer great promise for high-power and high-temperature applications due to the materials’ superior electronic properties. In this report, we will present results on the development of thermally stable Schottky contacts for high-temperature applications. The effects of rapid thermal annealing on the electrical and materials characteristics of iridium Schottky contacts on n-type GaN and Al0.25Ga0.75N were investigated. Emission was obtained from vacuum evaporation (LV) and capacitance-voltage (CV) measurements for diodes upon annealing in nitrogen ambient at temperatures varying from 400 °C to 850 °C. Electrical characteristics (effective barrier height, ideality factor and reverse leakage current) of diodes on Al0.25Ga0.75N were found to be stable for annealing temperatures up to 700 °C, while the diodes on GaN exhibited degradation at 500 °C. We will present results from further examination of the iridium Ir/AlGaN n-systems developed by means of x-ray diffraction spectroscopy as well as the detection of possible intermetallic and interface reaction products by x-ray diffraction (XRD) and x-ray photoelectron spectroscopy (XPS), respectively. Results show the potential for using iridium Schottky contacts for the fabrication of GaN-based transistors for high-temperature applications.

Y5.42
High reflective Ni/Al ohmic contact on p-type GaN using Ag rear mirror for flip-chip LEDs. Sae Young Kim, Hae-Ki Yoo, Ho-Won Jung and Jong-Lam Lee, Department of Material Science and Engineering, Pohang University of Science and Technology (POSTECH), Pohang, South Korea.

Nitride semiconductors are crucial materials for short-wavelength optoelectronic devices, such as light-emitting diodes (LEDs), photodetectors, laser diodes and so on. In conventional top-emission LEDs, a large fraction of photogenerated carriers from the active region are lost due to the high index of refraction. As a result, the quantum efficiency of the LEDs is low, and the quantum efficiency of the LEDs is low. To reduce the quantum efficiency and current spreading problem, fabricating a flip-chip (top-emission) type of device is important. The low reflective Ag metal was deposited on the p-type GaN substrate to improve the quantum efficiency and the current spreading problem. In this letter, we report on an oxidized Ni/AgNi/ITO/Ag ohmic contact with low resistance and high reflectance on p-type GaN. For evaluation of the contact resistivity on p-type GaN, a TLM test structure was formed. Ni (20 Å) and Au (30 Å) metals were deposited in sequence by electron beam evaporation, followed by pre-annealing the Ni/Au metal at 500 °C under O2 ambient (reference sample). Then, the sample was made by depositing Ag (300 Å) film on the reference sample by RF magnetron sputtering, following by depositing Ag or Al (300 Å) by thermal evaporation. After annealing at 500 °C under O2 ambient, a specific contact resistivity as small as 3 x 10^-4 Ω cm^2 was obtained using Ni/AgNi/ITO/Ag. The contact resistance of Ni/AgNi/ITO/Ag contact was higher than Ni/AgNi/ITO/Ag contact by a factor of 10^-3. The X-ray diffraction profiles and Auger electron depth proﬁles showed that the ITO layer acts as a diffusion barrier for diffusion of Ag into the Ni/AgNi/ITO/Ag layers, providing the low reflective and high reflective ohmic contact on p-type GaN for flip-chip light emitting diodes. Therefore, it is considered that Ni/AgNi/ITO/Ag contact could be a promising p-contact for a reflective ohmic contact to GaN-based flip-chip LEDs.

Y5.43

A novel GaN light-emitting diode (LED) structure employing an omnidirectional reflector (ODR) using rare-earth conducting metal oxides is presented. The triple layer of the ODR consists of p-type GaN, quarter-wave thickness of RuO2 or IrO2 and silver layer. The RuO2/Ag and the IrO2/Ag contacts serve as ohmic contacts to the p-type GaN. It is shown that the ODR-LEDs have higher light-extraction efficiencies, better electrical properties and thermal stabilities than the LEDs with conventional Ni/Au contacts and IrO2/Ag contacts. The GaN:LED structure was grown by metallocrystal chemical vapor deposition on c-plane sapphire substrate and consists of a thick n-GaN buffer layer, an n-GaN lower cladding layer, a GaN:Ni/GaN multiple quantum well active region, a p-GaN upper cladding, and a highly doped GaN cap layer. LED structures were obtained by dry-etching. Ti/Al/Ni/Au ohmic contacts to n-GaN were deposited and annealed at 600 °C under N2 ambient. Then, Ru or Ir was deposited on p-GaN and annealed at 400 °C under O2 ambient to form quarter-wave thickness of RuO2 or IrO2 respectively. Finally, Ag reflecting layers were deposited. For comparison, LEDs with conventional Ni/Au and ITO/Ag contacts on p-type GaN were fabricated on the same wafer. High-resolution x-ray diffraction and x-ray photoelectron spectroscopy results show that metallic Ru and Ir contacts transformed to virtually RuO2 and IrO2 after the oxidation annealing. RuO2 and IrO2 contacts to p-type GaN show much lower contact resistivity than ITO/Ag contacts and are comparable to conventional Ni/Au contacts. In addition, the light power extracted from the ODR-LEDs is significantly larger than from conventional LEDs. This can be attributed to both better light extraction and the high reflectance of the RuO2 or IrO2 contacts. Finally, the polarity and IrO2 layers restrain the degradation of contacts due to the diffusion of silver into p-type GaN surface at an elevated temperature, leading to a good thermal stability of the GaN ODR-LEDs.

Y5.44
High Quality Metal/Tin Oxide Ohmic Contacts to p-type GaN, Dong-Seok Lee1, J. Oh, Dong-Jin Kang, Hyun-Min Jeong, H. N. Norm, Y. Park2 and T.Y. Seong3, 1Department of Materials Science and Engineering, Kwangju Institute of Science and Technology (KIST), Kwangju, 500-712, South Korea, 2Photronics Lab., Samsung Advanced Institute of Technology, Suwon, 443-600, South Korea.
Formation of high quality ohmic contacts to p-GaN is one of the key issues for the further improvement of the performance of optical devices such as high power LEDs and LDs. The ohmic contacts are currently being used as ohmic contact electrodes for commercial LEDs. However, this contact is required to improve thermal stability and transparency. Recently, reliable ohmic metallization schemes using transparent conducting oxides (TCOs), such as indium tin oxide (ITO) and Al-doped zinc oxide (AZO), have been investigated. In particular, the use of AZO (45θm) was found to be fairly effective in improving the electrical and optical properties of ohmic contacts. In this work, we have used various tri-metallization processes based on TCO(s), such as Ni/Ti oxide [SnO2] and Ru/Ti oxide [SnO2], for producing high quality ohmic contacts to p-GaN (5e10 cm−2). It is shown that both the contacts show linear current-voltage characteristics with increasing measurement temperature. Measurements show that specific contact resistances are in the range of 10−3Ω cm at 450–550°C in air ambient. The light transmission of the contacts is shown to be comparable to other schemes reported at wavelengths in the range of 450–550 nm based on x-ray photoelectron spectroscopy and Auger electron spectroscopy results. Possible mechanisms for the formation of oxidized metals/TCO ohmic contacts are described and discussed.

Y.5.45

Despite the significant progress made in the development of UV emitters, the fabrication of UV LEDs and laser diodes remains a challenging problem due, in part, to the difficulties encountered in the growth of high-quality AlGaN layers. AlGaN layers must be grown with reduced defect densities and high levels of both n- and p-type doping. Here, we report on detailed temperature dependent, time-resolved photoluminescence (PL) studies of Si-doped AlGaN epilayers. In these samples, the Al fraction varies from 26% to 66%. The samples were found to exhibit metallic-like temperature-independent conductivity. The deep level "yellow" emission, whose presence would indicate the existence of a large number of defects, was not observed. Si incorporates well in the AlGaN matrix and no alloy formation is apparent. In addition to emission corresponding to the donor-bound exciton, the PL spectrum exhibits features associated with transitions involving localized carriers. This assignment of the emission mechanisms is based on the activation energies extracted from the temperature dependent photoluminescence quenching. Specifically, at room temperature the PL spectrum is dominated by transitions involving localized states. The localization energy varied from sample to sample and was observed to be between 110meV to 281meV. The excitonic PL decay time was 0.5ns at 15K and decreased to 0.1ns at room temperature. These measurements indicate that the exciton concentration is reduced to below 1%. Al mole fraction AlGaN epilayers grown by plasma-enhanced molecular beam epitaxy without quenching of the band edge UV emission. These Si-doped AlGaN layers can be used as active layers in light emitting diode structures.

Y.5.46
Effects of surface passivation in AlGaN/GaN heterostructure field effect transistors. Chiew Min-Jer, Jin-Hoon Lee2, Jung-Hee Lee2, Mi-Ran Park2, Kye-Suk Lee3 and Jong-Lun Lee1; 1Minerals Science and Engineering, POSTECH, Pohang, Gyeongbuk, South Korea; 2Electronic and Electrical Engineering, Kyungpook National University, Daegu, Gyeongbuk, South Korea; 3Electronics and Telecommunications Research Institute, Daejeon, ChungNam, South Korea.

The AlGaN/GaN heterostructure field effect transistors (HFETs) have been considered as one of the most promising candidates because of their potentially superior performance for high power and high frequency electronic devices. It has been reported that surface passivation with a dielectric such as amorphous silicon nitride can greatly reduce the amount of trapping in a HFET, resulting in significant improvement of available output power performances. These improvements could be due to the reduction of the traps, either bulk or surface, which cause loss of output power. However, the AlGaN/GaN heterostructure devices sensitive to strain and the passivation layer of amorphous silicon nitride can affect the AlGaN layer with the strain. Thus, it is important to investigate the effect of surface passivation in AlGaN/GaN HFET in terms of traps for electrons injected into the AlGaN layer by silicon nitride. However, no works has been conducted on the effect of strain in AlGaN/GaN HFET with surface passivation. The maximum drain current density (Jmax) of AlGaN/GaN HFET was dramatically increased by 11.9% after the passivation of 500 nm-thick-silicon nitride. In order to investigate the mechanism of effects in surface passivation, the stress measurement, deep level transient spectroscopy (DLTS), and electron-beam induced current (EBIC) were used. The stress measurement shows that the curvature-radius of AlGaN layer on heterostructure decreased from 19.08 to 17.01 mm corresponding to 12.17%. It means that the tensile strain applied to the AlGaN layer increase and the 2 dimensional electron densities at the interface of AlGaN and GaN also increase due to the piezoelectric effect by the passivation. The surface trap densities for electrons decreased by the silicon nitride passivation. From these analyses, the effect of surface passivation in AlGaN/GaN HFET will be discussed.

Y.5.47

Two main methods are used for InxGa1-xN growth: high-temperature Metalorganic Chemical Vapour Deposition (MOCVD), proven to be successful for the growth of materials for commercial devices with low InN content (x<0.3), and low-temperature Molecular Beam Epitaxy (MBE), with better prospects for obtaining higher InN fractions (x>0.5). A direct comparison between MOCVD and MBE InGaN epilayers with similar InN concentration has been performed for the first time. The InN fraction in available MOCVD epilayers varies from 0 to 0.4 while in our MBE samples the range is 0.15-0.35. Wavelength Dispersive X-ray (WDX) analysis and Extended X-ray Absorption Fine Structure (EXAFS) spectroscopy were performed to determine the composition of the samples. In-situ cathodoluminescence (CL) and ex-situ photoluminescence (PL) energy mapping were combined with large-area spatially resolved absorption spectroscopy to investigate the optical properties of the materials. The composition dependencies of the optical energies are found to vary with the growth method. The trendline of absorption bandgap and PL/CL peak energy for InN fraction is linear in both cases. The energy obtained for zero InN concentration in MOCVD epilayers is close to the wurtzite GaN bandgap of 3.4 eV at room temperature, while the equivalent figure for InxGa1-xN samples is below 3.2 eV. We will attempt to explain this behavior.

Y.5.48

Polarized infrared reflection from 300 to 1200cm−1 at different incidence angles was measured for sapphire and GaN/sapphire samples. The approximately 1300nm thick film of GaN was grown on c-plane sapphire by MOCVD without a buffer layer. Because of the hexagonal structure of GaN and sapphire, their optical properties are anisotropic. In the p-polarized reflective spectrum, we can observe the mixed effect between the distinct infrared-active modes with dipole-moment oscillation perpendicular (E-mode) and parallel (A-mode) to the c-axis. The contribution of the A-mode increased with increasing incidence angle. Therefore, we were able to obtain simultaneously the infrared dielectric functions parallel and perpendicular to the c-axis, by fitting simultaneously three polarized reflection spectra at three different incident angles with suitable model. In the procedure, we adopted a new fitting technique, which we had proposed previously [1], i.e., fitting the first numerical derivative of the polarized reflection spectra to improve the accuracy of the phonon parameters and to overcome the inconsistency between the model and measurement in the whole frequency range. Excellent agreement has been obtained between the measured and fitted first derivative reflection spectra for both the sapphire and GaN/sapphire samples. The dielectric information obtained for sapphire and GaN are of greater accuracy than those reported previously [1]. G. Yu, N. L. Rollow, D. J. Lockwood and Z. R. Wasilewski; submitted to Applied Physics Letters.

Y.5.49
Prism-Coupling Measurements of the Refractive Index and Birefringence of InGaN Layers Grown on GaN films. Nathan A. Sanford4, M R. Holic3; 4Optoelectronics Division, National Institute of Standards and Technology, Boulder, Colorado; 5Lumileds Lighting, San Jose, California.

Prism-coupling methods combined with multilayer birefringent waveguide analysis were used to measure the ordinary and extraordinary indices of refraction of InxGa1-xN layers that were grown on GaN films. S kiss error (988) was used to assess the InMOCVD growth of all the InxGa1-xN/GaN structures examined.
Several samples were studied with $x$ varying from 0 to 0.08. The film was estimated using x-ray analysis and photoluminescence. X-ray interference fringes limited the film thickness range to approximately 300 nm. The thickness of a typical GaN layer was approximately 1300 nm. The measured mode effective indices of ordinary and extraordinary polarized waveguide modes launched into the InGaN/GaN/GaN films were used as inputs in least-squares solution procedures to solve for the film thickness, refractive index, and birefringence. Data was collected at several discrete wavelengths from 442 nm to 622 nm with the blue end of the measured wavelength range being cut off by the cold finger (ruffle) prism. Results for samples with $x = 0.08$ will be presented at the meeting.

Y.5.50
Interband Emissions in AlN/GaN Quantum Wells Probed by Photoluminescence

Mahmood Islam, Swapan Nath, and Syed A. Choudhury

With a large band offset between AlN and GaN, the conduction band (about 1.9 eV) and the valence band are completely separated (about 2.7 eV). This and the large bandgap (about 3.5 eV) make AlN/GaN one of the most promising materials for high performance optoelectronic devices. In the last few years, much interest has been focused on the application of these materials in quantum well structures. In these structures, the interband transitions are very important for the study of new types of devices, such as quantum cascade lasers. In AlN/GaN quantum wells (QWs), the transition energies are tunable by tuning the well width. The quantum wells can be used as laser devices, and the interband transitions can be used as optical sources. In this work, we have studied the interband transitions in AlN/GaN quantum wells using photoluminescence spectroscopy.

Y.5.52
Optical Properties of $N$- AND Ga-Polarity GaN

J. L. Smits, F. A. Ponce, and F. M. Duan

A GaN sample with $N$-polarity GaN and $N$-polarity N was grown by molecular beam epitaxy (MBE) on a sapphire substrate. The sample was then annealed and characterized using photoluminescence spectroscopy. The results showed that the $N$-polarity GaN and $N$-polarity N have different optical properties. The $N$-polarity GaN has a higher electron mobility and a lower defect density compared to the $N$-polarity N. This suggests that the $N$-polarity GaN is a better material for high performance optoelectronic devices. In addition, the $N$-polarity GaN has a higher luminescence efficiency and a lower photoluminescence linewidth compared to the $N$-polarity N. This suggests that the $N$-polarity GaN is a better material for high efficiency light emitting devices.
3.43 eV, preliminarily attributed to an excited bound to the neutral shallow donor and unidentified structural defect, respectively. The quantum efficiency of the excited-relaxation onset exceeds 10%, whereas that of the combined emission from the defect-related bands (red, yellow and blue) is below 0.1%. Excitation of the PL spectrum with temperature and excitation intensity is analyzed in detail. Effects of polaron and exciton correlations on the PL properties and surface morphology will be also discussed.

Y5.54 Carrier Dynamics of Monolithic InGaAs/AlGaAs Light-Emitting PN-Junction Structures with Two Active Regions, Yun-Li Li1, J. M. Shah1, Th. Gessmann1, E. F. Schubert2 and J. K. Sheu2, 1Electrical, Computer, and Systems Engineering Department, Rensselaer Polytechnic Institute, Troy, Massachusetts, 2Optical Science Center, National Central University, ChungLi, Taiwan.

The most energy-efficient way to generate white light is the mixing of two or more primary colors. We show in this work, that in the yellow-green region of the visible spectrum, efficient monolithic solid-state white light sources can be demonstrated by using quantum well structures emitting at two wavelengths. In this work, monolithic InGaAs/GaAs light-emitting pn-junction structures with two active regions grown by metal-organic chemical vapor deposition are investigated. In addition, the carrier dynamics of such quantum well structures is analyzed. Room-temperature and low-temperature photoluminescence and room-temperature electroluminescence measurements show two emission bands originating from the two active regions. We find markedly different emission characteristics for photo-pumped and current-injected excitation. In photo-pumped experiments, the intensity ratio depends strongly on the excitation level whereas for current-injection, a constant intensity ratio is found. The independence of spectral shape on the injection current is a favorable property in results in emission color independent of the injection current density. The dependency of the emission on excitation is discussed and attributed to carrier transport between the two active regions and to the different carrier injection dynamics in photoluminescence and electroluminescence. The theoretical luminescence efficiency of a grainless dichromatic white-light source is calculated assuming a line broaden ranging from 2.25 to 10.0 kT. Luminous efficiencies ranging from 380 to 440 lm/W can potentially be obtained for broadened dichromatic sources, indicating that very high luminous efficiencies could be reached with dichromatic light-emitting diodes.

Y5.55 Structural Defect-Related Photoluminescence in GaN.
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Broad, low temperature photoluminescence (PL) peaks near 3.43-42 eV in GaN have been extensively associated with structural defects and in particular by planar stacking faults, based on empirical correlations between transient electroluminescence and photoluminescence. Theoretical studies have observed unusual sharp and highly structured PL peaks in this region in high quality bulk GaN grown from a Na/Ga flux, some of which display characteristic shifts and narrowing as a function of excitation power. Here, we study the behavior of these peaks as a function of excitation intensity, temperature, and crystal polarity, and compare them to those observed in GaN grown on SiC or sapphire substrates by metalorganic chemical vapor deposition (MOCVD). We find very similar spectral characteristics in all samples, including the peak wavelength, lineshape, and most importantly, the connection to the structural defect. The peaks in the off-axis material do not generally show the shifts with excitation power observed in the bulk samples. We describe a preliminary model for these features based on spatially indirect recombination at 3C quantum wells embedded in the 6H matrix. Band bending is present due to the spontaneous polarization in the 2H phase, which is absent in the 3C layers. The laser excitation flatters the bands to some degree, producing the observed shifts.


Optical characterization of AlGaAs-GaAs with different Al compositions was undertaken to investigate the importance of deep defect-related states and alloy fluctuations on the photoluminescence lifetime and the subsequent suitability of these materials for ultraviolet light emitting devices. Sub-nanosecond time-resolved photoluminescence (TRPL) was used to determine the growth of Ryerson's assisted molecular beam epitaxy on thick hydride vapor phase epitaxy GaN templates. Observations of nominally x = 0.10 and x = 0.20 Al content epitaxial show room temperature lifetimes of 0.50 ps. These half-life measurements are consistent with the TRPL signals of the GaN templates, which had estimated defect densities in the mid 1014-1015 cm-2 range, and are better than values found for AlGaN on sapphire (less than 20 ps), with presumably higher defect densities. This suggests that the bulk defects are shallow and one of the carriers is thermally activated such that the TRPL decays are dominated by trapping in deep defect states. By comparison, measurements of a nominally x = 0.40 Al content epitaxial showed degradation of the lifetime to ~7 ps. Moreover, at lower excitation densities, the lifetime becomes significantly shorter (~25 ps), indicating the presence of a natural defect not as evident in the lower concentration samples. This behavior implies that the carriers are trapped in bandtails with activation energy larger than 1 eV, and are funnelled through those states to the deep defect levels. Also, the intensity dependence implies that it is this decay path through the bulk states that saturates, which in turn shows the emergence of alloy fluctuations as a significant contributor to the carrier dynamics and optical properties of higher Al concentration material.

Y5.57 Ultrafast Carrier Dynamics in MBE Grown InN Epitaxial Layers, Fei Chen1, Alexander N. Cartwright2, Hsi Li3 and William J. Schiff2, 1Department of Electrical Engineering, University at Buffalo, State University of New York, Buffalo, New York, 2Department of Electrical and Computer Engineering, Cornell University, Ithaca, New York.

Ultrafast two-color differential transmission measurements on a series of InN epitaxial layers, with various free electron concentrations, grown by molecular beam epitaxy have been employed to probe the carrier recombination dynamics and hot carrier relaxation processes in these materials at room temperature. These measurements were performed with a pump energy of 1.55 eV and probe energies varying from 0.6 eV to 1.0 eV. The peak energy of the charge excitation was consistent with the 0.7 eV bandgap recently reported in these materials. Moreover, we observed a fast initial hot carrier cooling to the lattice temperature followed by a slower recombination process after pulse excitation. At short time delays, modeling of the observed relaxation suggests that the dominant energy relaxation process is longitudinal optical phonon scattering modified by a strong hot phonon effect. At longer times, a redshift of the peak energy in the differential transmission spectra was observed. This redshift is consistent with a reduction of the band filling effects that occurs as the photoexcited carriers recombine. Furthermore, our results demonstrate that the room temperature carrier lifetimes in these materials are inversely proportional to the free electron concentrations. This suggests that the donor-like defects or impurities may stimulate a formation of non-radiative recombination centers reducing the carrier lifetime. Most importantly, carrier recombination times were observed, indicating high crystalline quality. Thus, the observed long carrier lifetime and strong photoluminescence at room temperature makes these InN crystals excellent candidates for the infrared emitters.
peaks involving the two-dimensional electron gas. These pronounced bands are energetically located below the typical bound and free electron lines. A clear magneto-absorber, associated with the interband transitions, whose intensity and location vary with the magnetic field. In terms of population effects and many-body interactions, these magneto-optical effects are analyzed.  

Y.5.50  
Optical and microstructural evaluation of pretreated InGaN quantum well structures.  
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In order to optimize the quantum efficiency of InGaN quantum wells for visible light, a clear magneto-absorber, associated with the interband transitions, whose intensity and location vary with the magnetic field. In terms of population effects and many-body interactions, these magneto-optical effects are analyzed. Considering effort has been devoted in recent years to the study of structural and optical properties of hexagonal and cubic InGaN epilayers. The motivation behind these investigations is the fact that the InGaN ternary alloy is the active medium in the highly efficient quantum-well structure emitting diodes and laser diodes operating in the short-wavelength UV spectrum. Despite these important applications, the light emission process of the device is still a matter of controversy in the literature. There is strong evidence that an important emission mechanism originates from plasma-allowed transitions in the InGaN alloy decomposition taking place in the InGaN layer. It has been recently shown that the laser separation can be suppressed due to biaxial stress in InGaN quantum wells. It is also well-known that the biaxial strain can be a driving force for order formation. Moreover, chemical ordering on the group-III sublattices of InGaN has also been reported. It is already known for various III-V semiconductors that long-range, or short-range, ordered stoichiometric inter-semiconductor correlations can be more valuable than the disordered alloy in certain growth temperatures. Therefore, a deep understanding of the role played by strain on chemical separation and ordering formation in InGaN layers is highly desirable. The control of strain parameters is important to monitor the QDs formation in the active region of the devices. We present a rigorous theoretical study of the effects of biaxial strain on the ordered phases formation in cubic InGaN alloys. The calculations performed here are based on a 4D pseudo-potential plane-wave method, within the framework of the density functional theory and the local density approximation, and a cluster expansion method together with Monte Carlo simulations. We compare our results with data collected from transmission electron microscopy, x-ray diffraction and micro-Raman spectroscopy measurements.

Y.5.62  
Parameters of acousto-optic interaction in AlGaN layers on sapphire and AlN substrates.  
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Surface acoustic waves (SAW), guided optical waves (GOW) in nitride films and their interaction have attracted a great deal of attention because of their potential applications for acousto-optic devices operating in blue and ultraviolet regions. We present the results of our investigations of the acousto-optic interaction between SAWs and GOWs in AlGaN layers grown by MOVCD on sapphire and bulk AlN substrates. We present the analysis of the layer and substrate properties corresponding to optimum conditions of the acousto-optic interaction. A large difference between the layer and substrate refractive indices for the AlGaN-on-sapphire optical waveguides causes multimode regimes of operation for typical layer thicknesses on the order of microns. In contrast, the single mode optical waveguiding can be only achieved in the structures containing AlGaN layers grown on bulk AlN due to the close values of the layer and substrate refractive indices. Also, the efficiency of the SAW excitation in such structures is considerably enhanced due to piezoelectric properties of the substrate.

Y.5.63  
X-Ray Diffraction and Raman Studies of Relaxation of Biaxial Elastic Strain in InGaN/GaN Nucleated on HVPE on SiC(0001) Substrate.  
Nicola N. Faleev, *c* I. Ahmadi *a* Mark Holtz, *b* Henryk Temkin, *b* and Yuri Melnik, *b* 1XRD, Rigaku/MSC, Inc., The Woodlands, Texas; *c* Physics, Texas Tech University, Lubbock, Texas; *b* Electrical Engineering, Texas Tech University, Lubbock, Texas; *b* TDI, Inc., Gaithersburg, Maryland.

Gallium nitride and related compound semiconductors are one of the most attractive wide-bandgap materials for the optical applications. Recent progress in growth procedures (MOVCD, MBE, HVPE, et al.) has greatly improved crystalline perfection of nitride materials. Nevertheless, crystal quality of III-V nitride heterostructures is still one of the most serious problems for further improvement of devices. Therefore investigations addressing the relationships between epitaxial growth conditions and defect generation in these materials are still urgent. We report detailed studies of GaN/SiC(0001) epitaxial structures using high resolution x-ray diffraction and Raman spectroscopy. Samples were grown by HVPE under the same conditions directly on SiC substrates without an AlN buffer layer. The thickness of GaN layers ranged from 310 nm up to 1600 nm. The initial thin (400 nm) GaN nucleation layer in order to accommodate mismatch of lattice parameters between substrate and epilayer structures. Preliminary results [A. Kuzminov, N. Faleev, H. Temkin et al., J. Appl. Phys. 89, 6092, (2001)] revealed that thin (300 nm) epitaxial layers are grown with very good perfection. Density of dislocations in the layer is less than 2×10^7 cm^-2.
very smooth surface at approximately 500nm after 20 minutes growth. Inside islands, TDs propagate from the NL at periodically distributed growth front. The first stages of the nucleation front between two islands, no TDs were observed in this region. TD bending towards the facets of islands occurred only before consequence. Very small voids existed near the bottom of HT-GaN nucleates with vertical walls. However, no TDs or dislocations were presented in late grown HT-GaN. The support of our work by AFOSR is greatly acknowledged.

Y.5.66

Manifestation of Structural Defects in Photoluminescence from GaN, Michael A. Redlich1, Peng Yan1, Jacek Jasiński2, Zurana Lëntjen-Weber1, and Hildas Mackov1. Electrical Engineering, VCU, Richmond, Virginia, 1Virginia, California.

A series of sharp intense peaks is sometimes observed in the low-temperature photoluminescence (PL) spectrum of unintentionally doped GaN in the photon energy range between 3.0 and 3.46 eV that are attributed to excitons bound to unidentified structural and surface defects. These unusual peaks are named Y lines due to the similarity of their properties to those of the Y lines in Li-VI compounds. Most of these peaks (at 3.31, 3.32, 3.34, 3.35, and 3.42 eV) are typically observed in GaN polycrystals. We analyzed X-ray diffraction data in a large set of GaN samples grown by molecular beam epitaxy in order to find any correlation between these unusual PL peaks and the GaN crystal structure. Moreover, in selected samples exhibiting strong Y peaks, cross-sectional transmission electron microscopy (TEM) was taken in an effort to detect the presence and density of various structural defects. The preliminary results indicate that at least some of the Y line structure in the grown material is not directly related to the observed structural defects, such as edge, screw, or mixed dislocations. However, there exists the possibility that point defects trapped at dislocations are responsible for these PL peaks.

Y.5.67

Raman Characterization of Strained GaN0.65As0.35 and In0.51 Ga0.49NyAs1-y Epitaxial Layers. Li-Jun Guo, Daniel M. Reed1, J.A. Gartlan and Z.H. Wei. Naval Research Laboratory, Washington, D.C., USA.

Pseudomorphically strained epitaxial films of the ternary alloy GaN0.65As0.35 have been grown on yGaN(100) with y ranged from 0 to 0.05. Samples of GaN0.65As0.35 y about 35 nm thick were grown both with and without a 5 nm GaN cap. Raman studies in quasi-one-dimensional geometry were performed on both capped and uncapped alloys. The phonon Raman spectrum displays two mode-like behavior. The GaN-like first order Raman modes are represented at y=0.05 by the strong longitudinal optic (LO) mode at 388.7 cm^{-1} and the weaker transverse optic (TO) mode at 208.4 cm^{-1}.

The alloying effect is also observed through two very broad disorder-induced acoustic bands at ~80 and ~170 cm^{-1}, indicating obvious atomic disorder within the crystalline network. Raman studies show a concentration increase of GaN-like LO bands towards lower wavenumber from 290.8 cm^{-1} at y=0 to 388.7 cm^{-1} at y=0.05. In addition, the GaN-like phonon band showed a proportionnal increase in its intensity and its frequency as the GaN concentration increases. Second order GaN-like Raman vibrational bands were also observed at 509, 534 and 570 cm^{-1} for y<0.05. The Raman shift and strain level, as characterized by x-ray diffraction, will be correlated for the GaN0.65As0.35 y samples. Raman results for the unstrained quaternary alloy In0.51Ga0.49N0.65As0.35 on GaN(100) will also be presented.

Y.5.68

Optical study of localized and delocalized states in GaNAs/GaAs. Zhongying Xu1, Xiongfei Luo2 and Weiyan Ge2.

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GaAs/ND semiconductor alloys grown on GaN substrate have attracted much attention due to their unusual physical properties and potential applications in long wavelength optoelectronic and photonic devices. Understanding the emission mechanism in these materials is very important, not only from the viewpoint of physical interest but also for the device design. In recent optical studies, the strong action of N atoms in GaAs and the GaN in between GaN and GaAs has not been shown to the absorption and photoluminescence (PL) very complicated. In PL measurements, related pair states, cluster states, localized band-tail states and delocalized states were reported in various waveguides. In the work, we use various optical techniques to study exciton localization and delocalization effects in GaNAs/GaAs system. The main results are: 1. Under short pulse laser excitation, we have observed a new PL emission from GaNAs/GaAs single quantum wells (QWs). It dominates the PL spectra under high
Y. 5.69

Strong dependence of the fundamental band gap on the alloy composition in InxGa1-xN and InxAl1-xN alloys.

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Ab initio total energy calculations, based on the full-potential augmented plane wave method within the local density approximation, are used to study the influence of alloying on the structural and electronic properties of cubic InxGa1-xN and InxAl1-xN ordered alloys in the clathrate- and zincite structures. We have investigated the lattice parameters and band gap energies. The lattice parameters, exhibit an upward bending of ~0.015 Å and ~0.15 Å, respectively for the InxGa1-xN and InxAl1-xN alloys. The composition dependence of the band gap is found to exhibit a small relative bowing parameter of 1.36 eV for InxGa1-xN. The band gap versus composition plot for InxAl1-xN alloys is well fitted with a large bowing parameter of 3.19 eV, and presents a direct to indirect band gap crossover at x (Al) = 0.83. The large bowing effect in InxAl1-xN alloys has been discussed in terms of a composition dependent bowing parameter.

Y. 5.70

Structural, energy gap, and thermodynamic properties of AlxGa1-xNy and AlxIn1-xNy systems.


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The group-III nitride semiconductors and their ternary alloys have been extensively investigated due to their importance for the electronic and optoelectronic device technology. Recent features are the opto-electronic commercial devices operating in the green-blue-UV spectral region. In this work, we present the results of ab initio calculations of the band structure and its band-gap properties of AlxGa1-xNy and AlxIn1-xNy ternary nitrides. We find that the band gap decreases from ~0.75 eV (InN) to ~0.3 eV (AlN). A way to enhance the flexibility of nitride alloys may be achieved by using AlxGa1-xNy and AlxIn1-xNy quaternary alloys. The use of AlxGa1-xNy and AlxIn1-xNy quaternary alloys is motivated by the fact that AlxGa1-xN and AlxIn1-xN have been found to be direct band gap semiconductors with band gaps ranging from 0.7 eV to 3.5 eV. In this work, we present the results of ab initio calculations of the band structure and its band-gap properties of AlxGa1-xNy and AlxIn1-xNy ternary nitrides. The calculations are performed using full-potential linearized augmented plane wave method within the framework of the density functional theory. The band structure calculations are performed for InN, GaN, and AlN. The obtained band structures are in good agreement with the experimental results. The band gaps of InN, GaN, and AlN are calculated to be 0.7 eV, 3.4 eV, and 7.6 eV, respectively. The calculations are in agreement with the experimental results. The band gaps of InN, GaN, and AlN are calculated to be 0.7 eV, 3.4 eV, and 7.6 eV, respectively. The calculations are performed using full-potential linearized augmented plane wave method within the framework of the density functional theory. The band structure calculations are performed for InN, GaN, and AlN. The obtained band structures are in good agreement with the experimental results. The band gaps of InN, GaN, and AlN are calculated to be 0.7 eV, 3.4 eV, and 7.6 eV, respectively. The calculations are in agreement with the experimental results. The band gaps of InN, GaN, and AlN are calculated to be 0.7 eV, 3.4 eV, and 7.6 eV, respectively. The calculations are performed using full-potential linearized augmented plane wave method within the framework of the density functional theory. The band structure calculations are performed for InN, GaN, and AlN. The obtained band structures are in good agreement with the experimental results. The band gaps of InN, GaN, and AlN are calculated to be 0.7 eV, 3.4 eV, and 7.6 eV, respectively. The calculations are in agreement with the experimental results. The band gaps of InN, GaN, and AlN are calculated to be 0.7 eV, 3.4 eV, and 7.6 eV, respectively. The calculations are performed using full-potential linearized augmented plane wave method within the framework of the density functional theory. The band structure calculations are performed for InN, GaN, and AlN. The obtained band structures are in good agreement with the experimental results. The band gaps of InN, GaN, and AlN are calculated to be 0.7 eV, 3.4 eV, and 7.6 eV, respectively. The calculations are in agreement with the experimental results. The band gaps of InN, GaN, and AlN are calculated to be 0.7 eV, 3.4 eV, and 7.6 eV, respectively. The calculations are performed using full-potential linearized augmented plane wave method within the framework of the density functional theory. The band structure calculations are performed for InN, GaN, and AlN. The obtained band structures are in good agreement with the experimental results. The band gaps of InN, GaN, and AlN are calculated to be 0.7 eV, 3.4 eV, and 7.6 eV, respectively. The calculations are in agreement with the experimental results. The band gaps of InN, GaN, and AlN are calculated to be 0.7 eV, 3.4 eV, and 7.6 eV, respectively. The calculations are performed using full-potential linearized augmented plane wave method within the framework of the density functional theory. The band structure calculations are performed for InN, GaN, and AlN. The obtained band structures are in good agreement with the experimental results. The band gaps of InN, GaN, and AlN are calculated to be 0.7 eV, 3.4 eV, and 7.6 eV, respectively. The calculations are in agreement with the experimental results. The band gaps of InN, GaN, and AlN are calculated to be 0.7 eV, 3.4 eV, and 7.6 eV, respectively.
of the chemical and coherent spinodals can be reconciled by appealing to recently developed perturbation theories that treat novel elastic effects occurring at the surface of the alloy, but distinct from the core-shell structure observed in the ensemble size as well as on the laser excitation power: the larger the ensemble size and the higher the laser power, the more shifted the PL. This phenomenon is documented in terms of laser heating and light scattering occurring in an ensemble of the GaN nanorods as almost linearly with the laser power; similar behavior was found for GaN film. A linear behavior is indicative of an excitonic rather than a bandgap emission. However, for the large ensembles the PL intensity exhibits a nonlinear saturation already at relatively low laser powers. Our findings will be discussed in terms of the optical properties of an individual nanorod as well as the collective. Cold temperature studies will be presented as well.

Y.7.45
GaN Nanorods: Are They Different from the Base Films?
Hye Won Seo1, Quark Y. Chen1, Xuefei Wang1, Wei-Kun Chu1, L. W. Tu1, C. T. Hikono2, T. W. Chi1, J. Lo1 and K. Y. Shiau1, 2
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Hexagonal in crystal structure, GaN was thought to grow well on a (111) silicon substrate due to similar plane symmetry. However, because of the high degree of lattice mismatch, GaN nanorods of various geometric parameters have been found on the base of the thin film. A natural question to ask then is how these spikes or nanorods are different from the base film. In this work, we conducted a comparative study on GaN films grown on (111) Si wafers by plasma assisted MBE. After low temperature buffer layer deposition at 500-600 °C, high temperature GaN growth was done at 720 °C. The nanorods were observed as bright spots on a dark background of the base film, which also carried its own strained surface morphology when inspected with different temperature and brightness. These slightly bright spots appeared semi-transparent, as the morphology of relevant area of the base film hidden behind the spots was still observable. We attribute the extra brightness of the spikes in the SE mode to the enhanced secondary electron emission, which arises from the geometric size effect as the scattered electrons have higher probability of escaping from an area of small radius of curvature. In the CL image mode, however, these rods are essentially all dark, while the base material shows as striated bright and grey interlaced. This suggests that the nanorods are indeed more perfect than the base film, as the energy bandgap of high quality GaN falls in the near-UV region, hence the base area, which gives out light more in the visible range, would have to more processing to allow for near infrared related processes before a lower energy radiative process takes place. There are, however, no distinguishable crystallographic differences between the nanorod and base area as judged from the similar EBSD Kikuchi patterns. The nanorods are sensitive to the laser beam irradiation. In this paper, we will also present the electron beam enhanced nanostructure formation and transformation. We thank James Meen for valuable discussion and technical assistance. This work was supported in part by the State of Texas through the Texas Center for Superconductivity at University of Houston, USA and in part by the National Science Council of the Republic of China.

Y.7.75
Perturbation-Induced Composition Instability in InN-Nitride Pseudo-Binary Alloy Films.
Stephen Roger Lee, Sundan National Laboratories, Albuquerque, New Mexico.

Composition stability in InGaN alloys is of broad interest for two key reasons. First, compositional instabilities may cause indium-rich domains, which are thought to localize carriers and enhance optical emission in InGaN quantum wells. On the other hand, compositional instabilities in high-indium-content InGaN may actually limit the ability to produce efficient light emitters in the deep-green region of the optical spectrum. Previous studies of compositional instability in InGaN have treated bulk-spinodal-decomposition models. The resulting chemical spinodal for InGaN predicts instability at 750 degrees C for In mole fractions within the range 0.9+/-0.2 but, the chemical spinodal overestimates the crystal temperature because it ignores elastic coherency strains. Extending the analysis to include bulk self-coherency strains yields the well-known coherent spinodal. Since bulk coherency strongly stabilizes the alloy, the coherent spinodal predicted for InGaN should be in fact stable at all temperatures and compositions. The opposing predictions of the chemical and coherent spinodals can be reconciled by appealing to recent developments in perturbation theories that treat novel elastic effects occurring at the free surfaces of the alloy, but distinct from the core-shell structure observed in the ensemble size as well as on the laser excitation power: the larger the ensemble size and the higher the laser power, the more shifted the PL. This phenomenon is documented in terms of laser heating and light scattering occurring in an ensemble of the GaN nanorods as almost linearly with the laser power; similar behavior was found for GaN film. A linear behavior is indicative of an excitonic rather than a bandgap emission. However, for the large ensembles the PL intensity exhibits a nonlinear saturation already at relatively low laser powers. Our findings will be discussed in terms of the optical properties of an individual nanorod as well as the collective. Cold temperature studies will be presented as well.

SESSION Y6: Characterization I
Chair: Kazumasa Hiramatsu
Wednesday 8 June
Room 312 (Hynes)

8:30 AM Y6.1
Polarization-dependent spectroscopy of the near-band-gap emission in free-standing GaN on Si wafer
Pham Thi Jaya, Christa B. Poon-Tay, Pawe1-Lof Holtz and Bo. Meier; IBM, Tjuborg University, Linkoping, Sweden.

Recently, with the availability of high-quality free-standing and homoepitaxial GaN layers, the accurate study of free- and bound-exciton emissions in GaN become possible. However, so far all of the experiments have been performed with a light wavevector k parallel to the c-axis and then the excitation of a dipole moment perpendicular to c-axis were probed. Here, we present results from a study of the edge emission (i.e. with a light wavevector perpendicular to the c-axis) in a free-standing HVPE GaN. Such geometry allows us to examine polarization properties of the optical transitions and to reveal exciton states with different symmetry. For the light polarized perpendicular to the c-axis, the low-temperature PL spectrum reveals the typical emission peaks of the acceptor-bound exciton at 3.496 eV and the donor-bound exciton at 3.4716 eV as well as a broad emission from the lower polariton branches of the A and B excitons. When the orientation of the detected light is parallel to the c-axis, quite different spectrum is obtained. Now, the dominant emission peak occurs at 3.4723 eV. Based on the temperature dependence, the peak is assigned as a donor-bound exciton involving a hole from the Bevalence band and its binding energy is found to be 8 meV. In this polarization, the free-exciton emission is dominated by the D exciton-phonon, but a strong enhancement of the emission arising from the lower polariton branch of the C exciton is observed with increasing temperature. The emission lines of the dipole-forbidden spin-triplet state and longitudinal state of the A exciton are also resolved in the spectra. The energies, relative intensities and temperature dependence of all observed peaks are analyzed in terms of the polarization selection rules and the exciton-polariton concept in a wurtzite crystals.

8:45 AM Y6.2
Optical properties of semi-insulating Fe-doped GaN substrates.
Olf Gellhaus1, M. R. Phillips1, E. M. Goldys2, R. P. Vivas3 and X. Xu4; "Microstructural Analysis Unit, University of Technology, Sydney, Sydney, New South Wales, Australia; 1Division of Information and Communication Sciences, Macquarie University, North Ryde, New South Wales, Australia; 2ATMI, Inc., 7 Commerce Drive, Danbury, Connecticut.

HVPE-grown GaN substrates with different Fe-doping levels were studied by UV-visible and infrared cathodoluminescence (CL) spectroscopy and monochromatic CL imaging. The CL intensity of the Fe3+ emission line at 1.266 eV (9T 01 A) internal transition) and its multi-phonon sideband structure were found to scale with the Fe-concentration and was even more pronounced at room temperature in samples with high doping levels 1x1019 cm-3. Conversely, the shallow donor bound exciton (D0X) emission intensity at 3.432 eV was reduced in the samples with higher Fe content. In the visible range, several defect emission bands with much weaker CL intensity were observed. The significantly lower CL intensity of the defect emission bands together with the unusual Fe3+ emission indicate that the GaN substrates are of high quality. Three defect bands were observed in the sample with the highest Fe-concentration, a blue luminescence (BL) band centered at 2.83 eV, the yellow luminescence (YL) band at around 2.93 eV and a broad green luminescence (GL) band centered at -2.45 eV. The GL is tentatively assigned to Fe-related defect complexes since it is not observed in nominally undoped HVPE-grown GaN. Monochromatic
CL imaging revealed a nonuniform distribution of the recombination centers responsible for the defect emission bands, where the spatial distribution of the 1Bl and the GL band are strongly correlated. In the infrared range, additional defect emission bands centered at \( \sim 0.89 \text{ eV} \) and \( \sim 0.84 \text{ eV} \) are observed in the moderately Fe-doped samples. These bands are not observed in the higher Fe-doped samples and attributed to Fe-related defect complexes rather than to Fe-related recombination centers.

9:00 AM Y6.3
Optical Properties of AlGaN Grown by Facet Controlled Epitaxial Lateral Overgrowth. Aigal Bell
1, R Liu
1, F A Ponce
1, S Kimiyama
2, H Amamoto
2 and I Akaike
2
1Physics and Astronomy, Arizona State University, Tempe, Arizona; 2Department of Materials Science and Engineering, Meijo University, Nagoya, Japan.

A big challenge for producing high performance ultraviolet light emitting diodes is the improvement of the quality of aluminum gallium nitride (AlGaN) buffer layer, specifically the nucleation layer in AlGaN need to be addressed. In this study, we use spatially resolved cathodoluminescence (CL) spectroscopy to study the optical characteristics associated with the complex growth evolution of AlGaN by facet controlled epitaxial lateral overgrowth (FACELO). In this case, crack free AlGaN films were grown on the inclined facets of a GaN template. 3H3n light emitting diodes have been successfully fabricated on these AlGaN films. The GaN template was deposited on sapphire at low temperature in order to produce the serpentine surface. The AlGaN was grown on the serpentine GaN facets until the film surface had planarized. TEM showed that a large density of dislocations is present at the boundary between GaN and AlGaN. The dislocations have been found to be due to but not limited to the dimension of temperature. The CL spectrum shown in the cross section shows GaN near band-edge emission at \( \sim 358 \text{nm} \) and broad emission from the AlGaN layer ranging from 350nm to 355nm. Monochromatic CL images show that GaN layer extends from the apex of the FACELO structure and 355nm emission originates from AlGaN that grows laterally from the serpentine GaN facet. These results show that aluminum is incorporated more readily when the growth front is in the plane face, compared with the inclined face. A second set of dislocations were observed by TEM on inclined boundaries within the AlGaN layer. The boundary between the regions of different aluminum composition corresponds to the location of the second set of dislocations. Laterally extended AlGaN dislocations with differing aluminum composition, appears to relax via the formation of dislocations.

9:15 AM Y6.4
Micro-characterization of the 2-dimensional Electron Gas in Pattern Overgrown AlGaN/GaN HEMT Structures. Jürgen Christen
1, Frank Bertram
1, Sven Helms
2, Stefan Keller
2, Steven P. DenBaars
3 and Unmesh K. Mishra
3
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Non-planar selective area growth (SAG) AlGaN/GaN HEMT structures were fabricated using metalorganic chemical vapor deposition pattern overgrowth. The \( Al_{0.3}Ga_{0.7}N/GaN \) two dimensional electron gas (2DEG) sandwich is grown on an AlN/GaN/InGaN/AlGaN heterostructure. After selective etching with SiO2 masks, deep etching is performed through the heterointerface into the GaN layer, leading to defined stripe geometries of 5μm, 50μm, 200μm, and 5μm wide ridges along the [110]-direction having 200μm pitch. Subsequent selective area overgrowth with \( Al_{0.3}Ga_{0.7}N \) occurs not on the masked ridges, but in the etched areas, and on the ridges sidewalls, exceeding the height of the original ridges. These AlGaN/GaN HEMT structures were optically and structurally characterized using spatially and spectrally resolved cathodoluminescence (CL) and atomic force microscopy (AFM). The laterally averaged CL spectra consist of several characteristic spectral features, the 2DEG emission from the GaN layer (\( E_{\text{2DEG}} \= 3.45 \text{ eV} \)), two emission bands from AlGaN (\( E_{\text{AlGaN}} \= 3.61 \text{ eV} \)), \( E_{\text{AlGaN}} \= 3.74 \text{ eV} \)) corresponding to two different Al concentrations, i.e. [Al] = 0.07 and [Al] = 0.1, respectively, as well as a faint second 2DEG emission from the lateral AlGaN-GaN/AlGaN/GaN heterostructure. The distinct change of the AlGaN emission energy directly visualizes the strong lateral Al composition gradient across the ridge. The modulation of emission energy of the 2DEG across the ridge is more complicated, however it can be best visualized by the HEMT structure. The small blue-shift, a strong red-shift and again a weak blue-shift can be found when moving from the planar region into the center of the ridge. The GaN at the ridge is topped by \( Al_{0.5}Ga_{0.5}N \), which is in addition to a 2DEG and additionally surrounded by \( Al_{0.3}Ga_{0.7}N \) at the side walk. Thus the ridge structure forms an additional lateral potential well for the 2DEG with distinct barriers in the slope region and a pronounced lateral confinement at the ridge edges and a pair of IDEG, e.g. quantum wires, running along the ridge is formed. The CL spectra of the 2DEG and IDEG emission are found to be widely independent of excitation density and their temperature dependence is discussed in detail.

9:30 AM Y6.5
Rabi Splitting Observation in a Bulk GaN Microcavity. Fabrice Sensand
1, Declan Byrne
2, Frank Naish
2, Mathieu Lecouy
2, Jean Missesser
2, Nidige Antoine-Vincent
2, A. Vason
2, Pierre Dussaux
2 and Joel Lemareille
2
1CRHEA CNRS, Valbonne, France; 2LASMEA Université Blaise Pascal, Clermont-Ferrand, France.

Recent results highlighted the potential of strongly coupled semiconductor microcavities to achieve a Bose condensate of polaritons in a solid state material [1]. This unique entity is of enormous interest from a fundamental point of view for the understanding of the non classical states of matter. This massive occupation of the lower polariton branch also has vast potential for a new generation of low threshold coherent light emitters, parametric amplifiers and optical switches [2]. Although the observation of the lower polariton branch has been observed in numerous material systems [2], these microcavities ultimately demand a material system having a large exciton oscillator strength and binding energy. A large exciton oscillator strength permits a large Rabi splitting resistant to exciton density and temperature broadening while a large exciton binding energy will be more resilient to the dissociation of polaritons into free carriers. The exciton binding energy in GaN-based microcavities [3] is 3meV for bulk layers and 5meV for quantum wells combined with their large coupling strength should produce robust polariton states that are stable at room temperature and at high exciton populations, potentially leading to a new generation of optoelectronic polariton devices. Very large Rabi splittings have been predicted theoretically but up until now there has been no report of strong coupling observation in a GaN-based microcavity. We report the first experimental observation of the strong coupling regime in nitride-based microcavity system. The nitride cavity consists of a /2 GaN layer sandwiched between a dielectric mirror and the silicon substrate, which acts as the bottom mirror. Reflectivity measurements have been performed under various angles of incidence at \( \theta = 5^\circ \), producing evidence of strong coupling behavior between the exciton and the cavity mode. A Rabi splitting of 31 meV is obtained experimentally. Transfer matrix simulations have allowed us to account for exciton recombination. Based on these calculations, the oscillator strengths of the A and B excitons are evaluated and these values are in good agreement with those previously determined in bulk GaN [1]. H. Deng, G. Weihs, C. Sensand, J. Bloch and Y. Yamamoto 298, 120 (2002). [5] M. Suba, C. Ciuti, J. Bloch, V. Thierry-Mieg, R. Andre, Le Si Deng, S. Kundermann, A. Mura, G. Bongiovanni, J. L. Shenli and B. Deveaud, Nature 414, 731 (2001).

10:15 AM Y6.6
Characterization of III nitride based Schottky UV detectors with Wide Detectable Wavelength Range (360-10 nm) using Synchrotron Radiation. Akihito Matsuda
1, Hisao Endo
1, Hironori Ishii
1, Masayuki Shirata
2, Hirono Watanabe
3, Hideo Miyake
3, Kazutoshi Fukuji
4, Yoshio Ohuchi
5, Jun-ichi Takano
2 and Yutaka Hamamura
2
1Department of Electrical and Electronic Engineering, Meie University, Tochigi, Japan; 2Research Center for Developmet of Frontier Information, Fuku University, Ibaraki, Japan; 3Photonics Research Laboratory, Mitsubishi Cable Industries, Ibaraki, Japan; 4Precision Equipment Company, Nikon Corporation, Tokyo, Japan.

High responsivity of Schottky detectors with wide detectable wavelength range (360-10 nm) are realized using III nitride based Schottky ultraviolet (UV) detectors consisting of GaN or AlGaN on AlN epitaxial layer. Vacuum UV (VUV) and Soft X-ray (SN) light is expected to new photolithography technique, such as using the light of an ArF laser (193 nm), an F2 laser (157 nm) and an EUV light (extreme UV, 13 nm). The fabricated III nitride based UV photodetectors have capabilities for being used in future 3D photolithography systems. Currently, for the detection of UV light, Si-based photodetectors are mainly used. However, they have significant limitations either due to the need of filters to stop low energy photons, their degradation and lower efficiency. III nitrides based photodetectors are expected to overcome these limitations.

Responsivity spectra of GaN Schottky UV detectors in near UV and VUV region (360-50 nm) are already reported [1]. However, the low responsivity in the VUV region due to shalow penetration depth is a problem for using in steppe. Furthermore, there are no reports on the responsivity spectra of GaN based UV detectors in SX region. The III nitride Schottky detectors with n-type nanowire electrodes grown by metalorganic vapor phase epitaxy (MOVPE). The Ni (1 nm)/Au (10 nm) Schottky contact is deposited on n-GaN or n-AlGaN on AlN. The responsivity spectra of UV detectors are characterized by measuring the photocurrent illuminating monochromatic 400 nm light at the beam line 3B1 (BL3B1) and 7B (BL7B) of the UVSOR.
In GaN-based blue LEDs, due to the presence of high density nonradiative defects including threading dislocations. In order to improve device performance, recombination dynamics in AlGaN—AlN alloys of wide ranges of x should be investigated precisely. In this work, radiative and nonradiative processes, which control the quantum efficiency, in nearly strain-free AlGaN—AlN alloy films (0.18<x<0.3) were studied by means of time-resolved (TR) photoluminescence (PL) spectroscopy making a connection with the results of positron annihilation measurements. The results obtained are following. (i) Steady-state measurements revealed that values of FWHM of the nonradiative PL peak were comparable to those predicted by the classical alloy broadening model, but the Stokes-shifts (SS) were as large as 100 to 250 meV. Both SS and the PL FWHM increased with increasing x until they reach their maximum around x≈0.7, indicating the presence of competition of formation of weakly-bound states in the alloys. (ii) From the results of temperature-dependent and TRPL, the localized excitons were found to delocalize with increasing temperature. (iii) Density of the column IV-H vacancies (V_{\text{H}}) in their complexes, and relative intensity of deep emission band (YI in GaN) compared to that of the near-band-edge emission at 300 K increased with increasing x up to 0.7. (iv) TRPL signals showed a biexponential decay at low temperature, and the slow component became longer and dominant with increasing x. Therefore, carriers are considered to be captured by certain trapping centers after the excitation, and subsequently detrapped and transferred to the localized states before radiative decay at low temperature. The increase of the slower lifetime and its dominance over the entire TRPL signal with the increase in x implied the increase of depth and concentration of the trapping level. Consequently, the TRPL signal became single exponential with increasing x due to the donor-acceptor pair recombination in the deep states. As a result, internal quantum efficiency decreased with increasing x for x<0.7. Therefore, realization of deep UV light emitting with AlGaN alloys can be expected due to further reduction of the nonradiative defect density as well as the V_{\text{H}}-related trap density.

11:30 AM Y6.10 Time-resolved Reflectivity Studies of Electric Field Effects in III-Nitride Semiconductors, Michael Weisbuch, H Shen\(^{1}\), A V Sampath\(^{1}\), C J Collins\(^{1}\), G A Garrett\(^{1}\), W L Barney\(^{1}\), Y Fedyunin\(^{2}\), J Chidsey\(^{3}\) and T D Mountain\(^{2}\) \(^{1}\) Sensors and Electron Devices Directorate, U.S. Army Research Laboratory, Adelphi, Maryland; \(^{2}\)ECE Department, Photonics Center, Boston University, Boston, Massachusetts.

Comparison of room temperature frequency dependence and nondegenerate femtosecond pump-probe reflectivity measurements reveal an additional component in the transient reflectivity (AR) decays for near bandgap probe that is attributed to a reduction of bandbending broadening due to screening of a surface electric field by photogenerated carriers. The effects of this field have been observed mostly dramatically in thin (~ 2 μm) MBE-grown N-polar GaN on sapphire, for which a peak field of ~200 kV/cm was obtained from Franklin et al’s oscillations in GaN. The normalized reflectance and X-photon frequencies observed by Raman spectroscopy indicate the presence of residual strain. Degenerate pump-probe measurements at 364 nm show a ΔR decay with a dominant ~85 fs decay time but nondegenerate experiments with pump at 385 nm and probe at 383 nm designed to minimize the electric field contribution indicate that the carrier lifetime in the band states is ~10 ps. These results therefore suggest that the long decay of the field screening observed with 365 nm probe provides a measure of carrier lifetime in deep trap states. The same measurements were performed on MBE-grown N-polar GaN on HVPE template with a total thickness of ~5.5 μm and surface field of ~10 kV/cm. This smaller field still leads to a significant change in the decay times for 364 nm (~310 fs) and 383 nm (~130 ps) probe. The decay time in the nondegenerate case decreases further for excitation of free carriers with 355 nm pump (~40 fs), thus suggesting for shallow trap states near the excitation resonance. In addition, this field screening provides a mechanism for generation and detection of acoustic phonon pulses in AlGaN epilayers on GaN templates that is used to measure the longitudinal sound velocity in bulk GaN and AlGaN as a function of Al content.

11:45 AM Y6.11 GaN—are Direction Dependence of Optical Properties in Epitaxially Laterally Overgrown GaN, Shidhar Shrivas\(^{1}\), Lijuan Geng\(^{1}\), Lingyun Shi\(^{1}\), Fernando A Ponce\(^{1}\), Frank Bertram\(^{1}\), Juergen Christen\(^{1}\), Yukio Narukawa\(^{2}\) and Shinji Tanaka\(^{2}\) \(^{1}\) Department of Materials and Astronomy, University of California, Santa Barbara, Santa Barbara, California; \(^{2}\)Institute of Experimental Physics, Otto-von-Guericke University, Universitzplatz 2, Magdeburg, 39106, Germany; "Nichia Corporation, 491, Oka Kaminoura, Amagasaki, Tottori-shi, 683-8601, Japan.

Threading dislocations are detrimental to the lifetime of GaN-based...
optoelectronic devices. Epitaxial lateral overgrowth (ELO) is a widely used technique to reduce the threading dislocation density in GaN. Although it has been demonstrated that ELO can reduce the leakage current of devices, many aspects of ELO are still not understood. In this work, we have correlated luminescence studies with microstructure and local carrier concentration in ELO GaN structures. The ELO structure was grown using MOVCD with SiO2 mask stripes parallel to a c\(\langle 1100\rangle\) direction. The resulting facet has two dominant growth fronts, the vertical growth along \(\langle 0001\rangle\) and the lateral growth along \(\langle 112\rangle\). We have found that the luminescence characteristics of these two growth fronts are considerably different. The lateral growth is characterized by a much brighter, blue-edge luminescence (BE) compared to the vertical growth. But the ratio of yellow luminescence (YL) to BE is considerably higher for the vertical growth. Comparison of CL and TEM images shows that the luminescence properties are related to the dislocation density. They depend only on the growth front. Micro-Raman measurements reveal a carrier concentration of 1 x 10^18 cm^-3 for vertical growth and 2 x 10^17 cm^-3 for lateral growth. The difference in carrier concentration explains the variation in luminescence intensities observed by CL. Our observations indicate that the differences are unlikely to be caused due to a differential incorporation of impurities. The variations are explained in terms of differences in the distribution of Ga vacancies. Ga vacancies are deep acceptors and would compensate the residual donors thereby reducing the recombination. They are also known to be responsible for YL in GaN. Variations in the concentration of these vacancies can cause differences in carrier concentration, and the relative intensities of BE and YL. Another reason for such a variation could be differences in local V/III ratios for the two growth fronts. The contribution of other factors such as surface kinetics is also considered.

SESSION V: Electronic Devices
Chair: John Zavada
Wednesday Afternoon, December 3, 2003
Room 312 (Hynes)
1:30 PM Y7.1
AlGaN/GaN HEMTs Grown by Plasma-assisted Molecular-Bead Epitaxy, Patrick Wakereji1, Christine Poblenz1, Siddharth Rajguru2, Feng Wu1, Andrea Corrion1, Umesh K Mishra1 and James B Specter1. 1Materials Science, UCSB; Santa Barbara, California; 2Electrical Engineering, UCSB, Santa Barbara, California.

We have studied structural and electrical properties of high-electron mobility transistors (HEMTs) grown on 4H-SiC(0001) by plasma assisted MBE. Growth was initiated by a 30-nm AlN nucleation layer deposited at 741°C under stoichiometric conditions. The substrate temperature was lowered to 715°C for the remaining growth. As-grown films were examined by atomic force microscopy, x-ray diffraction (XRD) and transmission electron microscopy (TEM) before HEMTs having 0.7 x 150 μm gate areas, Hall and capacitance-voltage (CV) patterns were measured. All measurements were performed at room temperature. Initially, we studied a series of 440 nm thick GaN buffers grown with different Ga fluxes (1.5, 3, 5 and 7x10E-7 Torr) on top of the AlN nucleation layer. The best structural properties based on off-axis x-ray diffraction rocking curves were obtained when Fig. 7, while the growth temperature was 111°C. The in situ growth rate was monitored using a high-resolution XRD. These films exhibited smooth surfaces with spiral growth between Ga-droplets. However, areas free of Ga droplets had a pitted morphology which was more pronounced with increasing substrate temperature. Hall measurements on these samples yielded carrier concentrations around 8 x 10^18 cm^-3 and mobilities exceeding 1400 cm^2/Vs for surfaces free from Ga-droplets. An increase in carrier concentration and a simultaneous decrease in mobility was observed when grown with Ga-droplets, thus, indicating parallel leakage at lower growth temperatures. The exact origin of this leakage (substrate surface, interfaces and/or Ga-droplet) is not yet understood. Furthermore, mobilities dropped with increasing surface roughness. These results indicated that temperature control and homogeneity are crucial during deposition. HEMTs exhibited source-drain currents, peak transconductances, and fmax around 1 A/mm, 200 mS/mm, 20 GHz and 35 GHz. Load-pull measurements were performed at 10 GHz with power densities exceeding 4 W/mm for SiN passivated devices. CV profiling evidences a GaN buffer background carrier concentration of 1 x 10^18 cm^-3. Current efforts are directed towards reduction of the buffer leakage utilizing deep-level impurity doping with carbon.

1:45 PM Y7.2

AlGaN/GaN based high power, high frequency heterostructure field effect transistors have been in development for more than ten years. At present, there exist several device concepts that are commercially available. Commercialization of this technology will require consistent, robustly scaled, and cost-effective technological and fabrication processes. The choice of Si as the substrate offers a platform that is of high quality (due to the maturity of the substrate material) and cost effective (due to the abundance of vendors and material). The technology of depositing GaN on Si has developed at a pace similar to that of GaN on other substrates. Epitaxial issues pertaining to the growth of device-quality GaN on Si include stress, material quality, and understanding of parasitic losses that can adversely affect the RF device performance. Improved device results are also contingent on the understanding of the impact of these growth issues on the device characteristics. We will report on the challenges associated with the MOCVD heteroepitaxial process of producing AlGaN/GaN HETs on Si and specifically address issues that affect and influence the nucleation process and properties that affect the performance of the GaN buffer layer. Growth parameters impacting nucleation and GaN buffer quality have been identified and their effect on the structural and electrical properties of the films and on device performance has been determined and will be discussed. Additionally, RF device results at VDS = 28V and f = 2.14 GHz presented that demonstrate transistor performance at the level needed to meet the emerging W-CDMA standards of the base station market.

2:00 PM Y7.3

GaN and related materials are very promising for high power, high frequency, and high temperature electronic devices. GaN devices with a lower on-state resistance on the Si substrate are effective for realizing low cost switching devices such as an inverter or a converter. In this paper, we report on the GaN/Si epitaxial growth using a metalorganic chemical vapor deposition (MOCVD) and a novel normally-off AlGaN/GaN heterojunction field effect transistor (HFET). We grew the GaN p-type Si (111) substrate using an AlGaN high temperature buffer without using a conventional low temperature buffer. A homogenous buffer layer was obtained at 1100°C. After that, AlGaN (30 nm)/high resistive p-type GaN (500 nm) heterostructure was also grown without cracking in a two inch wafer. Using a transmission electron microscope (TEM), we observed that the interface of GaN and AlGaN buffer was very smooth and the AlGaN/GaN hetero-interface was also smooth. We fabricated an HFET using AlGaN/GaN on Si substrate. The chthic electrode material was Al/Ti/Au and the gate electrode was Pt/Au. The distance between the source and the drain was 10 μm. The gate length and width were 2 μm and 150 μm, respectively. When the gate bias was in the range from 0 V to 5 V, the HFET was operated. The pinch-off voltage was 0 V. The gate leakage current was below 10^-10 A. A normally-off p-type GaN/Si heterostructure was also confirmed for the first time. The on-state resistance was about 10 mΩmm. The transconductance (gm) was about 20 mS/mm. The breakdown voltage was over 1000 V. We also confirmed that the normally-off HFET was operated as 5500 V for over 1.5 μm gate length. Normally-off GaN based HFET on Si substrate is very promising for switching devices.

2:15 PM Y7.4
High-Power Characteristics of GaN/InGaN Double Heterojunction Bipolar Transistors with a Regrown p-InGaN Base Layer, Toshiki Makimoto, Yoshishita Yamashita and Kazuhide Kumikura, Physikalische Science Laboratory, NTT Basic Research Laboratories, NTT Basic Research Labs., Atsugi, Kanagawa, Jpn.

Nitride heterojunction bipolar transistors (HBTs) are promising for high-power and high-frequency electronic devices due to the material and the device structure. Recently, we have successfully
fabricated GaN/InGaN double heterojunction bipolar transistors (DHBTs) with a regrown p-InGaN base layer. These DHBTs show a maximum current gain of 80000 at a collector current of 0.003 A, which is more than 10 times as high as our previous record [1,2]. In this conference, we will present the high-power characteristics of the DHBTs. The HBT structures were grown on SiC substrates using low-pressure metallocorganic vapor phase epitaxy (MOVPE). The DHBT structure consists of a 6μm-thick Si-doped GaN collector, a Si-doped graded InGaAlN base, a 10μm-thick Mg-doped InGaN intrinsic base, and a Si-doped graded InGaN emitter. The In mole fraction and thickness in the intrinsic base were 7% and 7μm, respectively. The Mg doping density of the Mg-doped 10μm-thick graded-InGaN was 2x10^{19} cm^{-3} and the corresponding hole concentration was 1.9x10^{18} cm^{-3} at room temperature. The regrown p-InGaN extrinsic base layer consists of 10μm-thick InGaN and 3nm-thick GaN. The alloy concentration was 9x10^{17} cm^{-3}. The common-emitter 1V characterization showed maximum current gain exceeding 20000 and the device with an emitter area of 50 μm x 30 μm operated up to a collector current of 80mA at a collector-emitter voltage of 50 V, corresponding to a current density of 270k W/cm^{2}. The HBTs showed a maximum current gain of 80000 at a collector current of 0.003 A, which is more than 10 times as high as our previous record [3]. This high-performance HBT is attributed to the suppression of heat generation during operation due to the improved base channel characteristics. This result also shows that the nitride HBTs are suitable for high-power electronic devices. [1] T. Makimoto et al. ICNSS-5, FrA12.6, Nara, May 2003. [2] T. Makimoto et al. DRC 2003, ILA-5, Salt Lake City, June 2003. [3] T. Makimoto et al. IJIMN 2002, 379, Ande, July 2002.

230 PM Y7.5
Strain Control and Carrier Confinement in Quaternary AlGaN/InGaN Heterostructure Field Effect Transistors. Remus Gaska1, Qihai Fu2, Rakesh Jain3, Ahmad Thrakjki1, Xuhong Hu1, Jinong Deng1, Michael Shur2, Grigory Simin3 and Afil Khan1;
1Sensor Electronic Technology, Inc., Columbia, South Carolina
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3Department of EE, University of South Carolina, Columbia, South Carolina.

In conventional AlGaN/InGaN heterostructure field effect transistors, the carrier confinement between the buffer and the active layer in this design is only due to the self-consistent triangular potential well at the interface, and carriers can easily spill over into the buffer GaN or the barrier AlGaN layers, especially at a high drain bias. The spilled over carriers get trapped and thus give rise to slow transient processes and to the famous RF-current collapse. Our comparative studies of DC-MESFETs with different channel doping and AlGaN/InGaN HFETs with various Al-content in AlGaN barrier [different band offset] showed that as much as 65-70% of the current collapse at RF frequencies is due to the spillover into the GaN buffer layer. Having InGaN channel in AlGaN/InGaN/InGaN DHFET design helped confine two-dimensional (2D) electrons close to AlGaN/InGaN heterointerface and prevent the electrons from spilling over to GaN and dramatically reduces the current collapse. Our studies showed that an efficient suppression of current collapse can be achieved when InGaN/InGaN/InGaN DHFET design. When the Al mole fraction in the barrier layer is increased in order to increase the electron sheet density in the channel, the carrier trapping in the AlGaN barrier layer becomes more important, and even the DHFETs might experience the current collapse. To prevent current collapse in 2D electron spill into the AlGaN barrier at high Al mole fractions, we developed a novel AlGaN/AlN/AlGaN/InGaN/AlGaN Triple HETF design with the InGaN channel separated from the high Al-content (over 30%) barrier by a non-intermediate barrier matching quaternary AlGaN/InGaN layer. The maximum RF power measured at 2 GHz frequency in HFETs and THFETs with nearly identical GaN buffer (similar trap density) was 3.4 W/mm and 0.6 W/mm, respectively. The obtained results clearly demonstrate potential of quaternary AlInGaN-based TFET approach for development of high RF power transistors. 2455 PM Y7.6 High-Spatial Resolution Thermal Imaging of AlGaN/InGaN HFETs for Assessment of Electric Field Device Modeling. Sekaran Rajasagaram1, Martin Kohali2, M. J. Uren3, T. Martin3, R. S. Bolster4, D. J. Walls2 and K. P. Hikos2;
1H. Wills Physics Laboratory, University of Bristol, Bristol, United Kingdom;
2QinetiQ Ltd., Malvern, United Kingdom.

Power AlGaN/InGaN heterojunction field-effect transistors (HFETs) are being developed for next generation mobile communication basestations, radar, and satellite communication. Knowledge of the electric field distribution is needed to optimize device design and performance. Since this is difficult to access in experiment, the electric field obtained using numerical techniques such as COMSOL is considered accurate. However, the accuracy of a specific model is difficult to validate. We illustrate here the use of high-spatial resolution thermal mapping of AlGaN/InGaN HFETs using micro-Raman spectroscopy to gain insight into the local electric field mappings of the example of a conventional AlGaN/GaN HFET. Micro-Raman spectroscopy allows us to measure the temperature distribution with less than 1μm spatial resolution, far superior to standard IR imaging techniques. Temperature distribution profiles in the device were obtained by increasing the drain voltage. The measurement of the electrical long channel model of Albrecht et al. [1] was used to calculate electric field distributions and current-voltage characteristics. Good agreement between measured and modeled current-voltage characteristics was observed. Although the model confirms the AlN barrier layer at the peak position with increasing source drain voltages, the model significantly overestimated the length of the high field region, i.e., the best agreement for the device was for small drain voltages. The results indicate a pathway for an assessment of the accuracy of the electric field distribution in device model. Acknowledgement: The QinetiQ contribution to this work was undertaken as part of the UK MoD Corporate Research Program. [1] J. D. Albrecht, P. P. Russer, and C. Bini, and M. G. Ancona, IEEE Trans. Electr. Dev. 47, 2031 (2000).

3:30 PM Y7.7 Ammonia-MBE: Growth of High Frequency GaN/AlGaN HEMTs and GaN/InGaN LEDs. James B Webb, Haipeng Tang and Jennifer A Birdwell; IMS, National Research Council Canada, Ottawa, Ontario, Canada.

The MBE growth of GaN materials and devices using ammonia as the nitrogen source has been a focus of research in our laboratory for the last five years. Several unique techniques have been developed to determine the AlN nucleation/blanket layer growth rate and the AlN epitaxial quality and epitaxy. To grow highly insulating carbon-doped GaN layers for use as the isolation buffer layer in HEMT devices. For the HEMT structures grown on sapphire substrates, room temperature mobilities were consistently above 10000 cm^{2}/Vs with optical phonons as the dominant source of scattering. High sheet densities up to 1.9 x 10^{13} cm^{-2} with mobilities still reaching 1000 cm^{2}/Vs have been achieved by increasing the Al concentration in the barrier to 10-15% without causing lattice relaxation. Fabricated HEMT devices with high sheet densities show saturation currents >1A/mm and peak transconductances of >200 mS/mm. Smaller devices grown on SiC substrates show a higher degree of performance. Considerably less self-heating is observed that those grown on sapphire substrates and the epitaxial layers are considerably smoother allowing for better control of optical and e-beam lithography. Devices with 0.13 μm gate length show an f_T of 100 GHz and an f_MAX of 1700GHz. Ammonia MBE in combination with Plasma MBE has also been recently studied for the growth of LEDs. Basic LED structures have been grown, covering the visible range of green to violet by changing the indium content of the GaN/GaN quantum wells. The potential for this growth technique in high performance optical emitters and detectors will be discussed.

4:00 PM Y7.8 Dielectric/Semiconductor Interface Characteristics of ILN Insulated Gate Field Effect Transistors. Alexei Koslymov
Husna Fatima, Shinva Rui, Shani Wu, Vinod Adwanshan, Gregoriy Simin and M. Afil Khan; Electrical Engineering, USC, South Carolina.

We present the first time a detailed characterization of SO$_2$- and Si$_3$N$_4$-AlGaN interfaces in the ILN-HFETs and IGFETs using a transmission dispersion technique. In addition, we present an extensive study of the use of Si$_3$N$_4$ as a surface passivation in the AlGaN/GaN HFETs, we show the surface charge density (SC) for Si$_3$N$_4$-AlGaN interface and surface charge density (SC) for Si$_3$N$_4$-AlGaN to be fairly high, around 6x10^{11} cm^{-2}. This is comparable to the 2D carrier sheet concentration. On the contrary, for the SO$_2$-AlGaN the SC is only 5x10^{11} cm^{-2} which is more than an order lower. Insulated Gate HFETs (IGFETs) have been demonstrated to have higher r-powers and significantly lower gate leakage currents than the conventional HFETs. In both cases (surface passivation or gate insulator), the device performance is affected by the dielectric/semiconductor interface quality. In our paper this quality was studied using submicron HFET and IGFET devices. HFET and IGFET structures with SO$_2$ and Si$_3$N$_4$ gate insulators were fabricated on i-ZIC substrates and data was presented. The dielectric was deposited using PECVD technique. Transfer characteristics were measured in the broad frequency range of 0.015 - 3x10^{11} Hz. To isolate the impact of surface/dielectric charging and current collapse, the measurement temperature regimen was used in small- and large-scale regimes. Since control over RF current collapse was used to extract the values of SC. Low SC in MOSFETs explains perfect gate control and close match between ILN and IGFET devices. At high SC, the surface charge at the Si$_3$N$_4$-AlGaN interface explains why passivation can affect current collapse. It also explains why control and reproducibility of this approach is poor. We will discuss alternative approaches to current collapse management.
4:15 PM Y7.9
Design of composite channels for optimized transport in nitride based heterostructure field effect transistors, Madhusudan Singh 1, Jasprit Singh 1 and Umesh K Mishra 2;

1Electrical Engineering and Computer Science, University of Michigan, Ann Arbor, Michigan; 2Electrical and Computer Engineering, University of California, Santa Barbara, California.

Heterostructure field effect transistors (HFETs) based on AlGaN/GaN structures have shown good performance as high power and high frequency devices. Theoretical simulations of transport in short channel HFETs are even more important where considerable improvements in mobility, etc. can be made if thin composite structures are considered in this work) can be utilized. The following outcomes of our computer simulations motivate this approach: (i) Due to the large electron effective mass and high scattering rates in GaN, low field electron velocities in short channel devices are very low. We find that velocities are below the steady state values calculated at the same electric field on the channel. (ii) Due to the very high scattering rates, the electrons do not display overshoot effects even at very high fields. To overcome the transport issues outlined above, we examine transport in a metal/AlGaN/InN/GaN composite structure. The InN region is very thin (~15 Å) and is introduced to improve the low field transport without significantly impacting the device breakdown properties. Our model is capable of examining any other type of composite structure as well. Our simulation method consists of charge control solution of the 2D Poisson equation, followed by Monte Carlo simulation of scattering and free flight events. We present comparison of results on i) metal/AlGaN/GaN structure; and ii) a metal/AlGaN/GaN structure with a channel of order of a few nanometers wide. We find that mobility in the channel can improve considerably with very little effect on the mobility - charge product. Indeed, the charge density induced in the thin InN channel region is ~10^13 cm^-2. While the peak velocities in metal/AlGaN/GaN structures are higher by a factor of 10^3 compared to metal/InN/GaN structures, an increase of nearly 30% over the values in metal/AlGaN/GaN structures, the low field mobilities are also increased. Low-field mobilities of 0.25000 cm^2 V^-1 s^-1 are predicted along with high sheet charges for low interface disorder for the structure with a thin InN layer. For higher degree of interface disorder (~70 Å), we have found good agreement with experimental Hall mobility data for similar structures. At higher electric fields, we find that most electron population transfer to higher valence or sub-bands that is, InGaN or GaN. This ensures that high field breakdown of low band gap InN layer is also suppressed.

4:30 PM Y7.10
Investigation of the electric field dependence of charge emission from traps in GaN/AlGaN/GaN HEMTs studied by transient current spectroscopy, esg microscopy, Michael Manfra and Nils Weimann; Bell Laboratories, Murray Hill, New Jersey.

RF dispersion continues to limit the power performance of AlGaN/GaN high electron mobility transistors (HEMTs). At this time, the exact value of the physical mechanism responsible for RF dispersion are not completely understood. While RF dispersion has been extensively studied in MOVCD grown layers, less data is available from MBE grown layers. Here we report on the effect of the electric field on the electron/HEMT interaction from the traps in unpassivated GaN/AlGaN/GaN HEMTs grown by MBE. Electron emission from the traps is studied using transient current spectroscopy. In this method, non-equilibrium concentration of the trapped charge is created when a short filling pulse is applied to the gate. The charge remains temporally localized on the traps after the filling pulse. Subsequent dynamics of the charge is measured through the source-drain current. We recently demonstrated unpassivated GaN/AlGaN/GaN HEMTs grown by plasma-assisted MBE with power densities exceeding 8 W/mm at 2 GHz. These results suggest that dispersion effects can be minimized with heterostructure design and MBE growth conditions. Nevertheless, our studies of gaseous in GaN/AlGaN/GaN HEMTs showed evidence of active charged centers on the surface and/or in the bulk of the heterostructure. Study of the temperature dependence of the dispersion indicated the thermal nature of the electron emission from the traps with activation energy of about 0.2 eV. We demonstrate that other factors such as drain-source bias can significantly influence the emission process. Electron emission from the centers has exponential character with the rate ranging from less than 1 μs at high fields to hundreds μs at low fields. The temperature dependence of the decay time (τ) follows a square root of the field. We will discuss physics of the active trapping centers, particularly, the structure, binding energy, and the mechanisms of charge capture and emission.

4:45 PM Y7.11
Experimental Analysis and a New Theoretical Model for Accurately High Quality GaN-Based p-n Junction Diodes, Jay Park, Y.L. Li, Th. Gesmon and E.F. Schubert; Electrical, Computer, and Systems Engineering Department, Rensselaer Polytechnic Institute, Troy, New York.

GaN-based p-n junction diodes. These values are much higher than expected from the Shockley-Read-Hall model, which predicts values of ~0.1-0.2. The high ideality factors (~2-3) in various x-ray and ultraviolet spectra of GaN-based light-emitting diodes have been attributed to tunneling. This attribution was motivated by the temperature-independent slopes of ~400 μA/cm^2, which was proposed a fundamental new model for the high ideality factors in GaN-based diodes. This alternative model is based on the concept of additional rectifying heterojunctions and metal-semiconductor junctions of the p-n junction diode. It is shown that the high ideality factors are due to heterojunctions as well as metal-semiconductor junctions, in particular the metal contact to p-type GaN, can increase the ideality factor of the p-n junction diode to values greater than 2. A relation for the effective ideality factor of a system of junctions is developed. It is shown that the ideality factor of the entire diode is related to the sum of the ideality factors of the individual junctions. A detailed study was presented on diodes fabricated from two structures, a bulk GaN p-n junction structure and a p-n junction structure incorporating a p-type AlGaN/GaN superlattice. The bulk GaN p-n junction diode displays an ideality factor of 6.9, whereas the one with the superlattice structure displays an ideality factor of 4.2. These results are fully consistent with the theoretical model and the fact that p-type AlGaN/GaN superlattices facilitate the formation of low-resistance ohmic contacts. In addition, the absence of the well-known excess current that is associated with tunneling further supports this new model.

SESSION 8: Doping/Theory

Thursday, December 4, 2003
Room 312 (Hynes)

8:30 AM Y8.1
Ordering in AlxGaxN-x alloys, L. Kalite, L. G. Ferreira, L. Scoforo and J. R. Leite; Materials Science, University of São Paulo, Physics Institute, São Paulo, Brazil.

Group-III nitride semiconductors, AlN, GaN, InN, and their ternary alloys have been successfully used in electronic and optoelectronic device technology. High efficient optoelectronic devices such as light emitting diodes and laser diodes, and high frequency high temperature electronic devices as field effect transistors, have been fabricated from these wide gap materials. The fabrication of devices needs high gap engineering. AlGaN is expected to be easier to fabricate than InGaN, since the lattice mismatch between AlN and GaN is the smallest between the III-V nitrides (~2.5%). Multiple ordering has recently been observed in AlxGaxN alloys by high-resolution x-ray diffraction and transmission electron microscopic experiments. It has been recognized that the basal strain can be a driving force for ordering formation. It is already well known for various III-V semiconductors that long-range, or short-range, ordered covalent inter-semiconductor compounds could be more stable than the disordered alloy below a certain growth temperature. Therefore, a deeper understanding of the mechanism that leads to ordered phase formation, as well as, the role played by strain on it in AlxGaxN alloy layers is highly desirable. We present a rigorous theoretical study of the ordering formation in relaxed and bistable strained cubic AlxGaxN alloys. These calculations are based on ab initio pseudo-potential plane-wave method, within the framework of the density functional theory and the local density approximation, and a cluster expansion method together with Monte Carlo simulations. Our results are useful for understanding of the observed ordered phase formation in AlxGaxN alloys.

8:45 AM Y8.2
Electrical and Optical Properties of Carbon Doped Cubic GaN Epilayers Grown Under Extreme Ga Excess, Dong J. Lee, David G. Parke, Joon, Sven Pothof and Klaus Lischin; Department of Physics, University of Paderborn, Paderborn, Germany.

Among possible alternative acceptor dopants in GaN especially Carbon has received considerable interest due to its similarity in nitrogen in atomic radius and electronegativity. Recently, we have shown that C is indeed the most promising acceptor in cubic GaN with a binding energy of about 215 meV. Unfortunately due to self-compensation effects the hole concentration saturated and then decreased with increasing C-flux with both macroscopic growth conditions. A C 8<2>/8>8 N 8<3>/8>8 complex is most likely responsible for the observed compensation. To avoid the formation of this complex Ga-rich growth conditions are proposed to increase the incorporation of C at the N-substitutional site. In the contribution we report in

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results using different secondary ions clearly confirm the existence of As-modulation in the GaN/GaAs structures. The modulation of As dopant strongly influences the optical properties of GaN/GaAs superlattices. PL spectra of both the blue emission and the band edge emission are modified with increasing of the period of GaN/GaAs superlattice and these changes will be discussed.

9:30 AM Y8.5
Optical Properties of Mn-doped GaN. Olaf Gehlhausen,1 E. Malguth,1,3 M. R. Phillips,1 E. M. Goldys,2 M. Strassburg,2 A. Hoffmann,2 3T. Graf3 and M. Stutzmann1
1Microstructural Analysis Unit, University of Technology Sydney, Sydney, New South Wales, Australia; 2Division of Information and Communication Sciences, Macquarie University, North Ryde, New South Wales, Australia; 3Institute for Solid State Physics, Technical University Berlin, Berlin, Germany; Walter Schottky Institute, Technical University Munich, Munich, Germany.

The optical properties of molecular beam epitaxy-grown GaN with different Mn-doping levels [5.3 x 1016 cm-3] were studied by UV-visible and infrared cathodoluminescence (CL) spectroscopy and optical transmission measurements. Transmission measurements at 2 K revealed an absorption peak at an energy of 1.414 ± 0.002 eV, which was attributed to a photoionization process by internal absorption from the Mn3+ ground state to an excited state. This assignment is supported by the absence of this transmission peak in GaN:Mn samples codeloped with Si, where an electron transfer process from the Si donor to the Mn acceptor takes place. The intensity of the Mn-related transmission peak was found to scale with the Mn3+ concentration. The CL measurements showed that Mn-doping concentrations around 1.5 x 1016 cm-3 under both the donor bound excitation emission intensity by more than one order of magnitude and also completely quenched both the shallow DAP band at 3.27 eV and the yellow luminescence centered at 2.2 eV. Additionally, the Mn-doped GaN exhibited a reducible structure sensitivity to electron beam induced charging was observed. In the infrared spectral range of 0.8 - 1.4 eV three broad, Mn-doped related CL emission bands centered at 1.13 eV, 1.08 eV and ~1.3 eV were observed, which were found to be highly beam sensitive. The GaN:Mn with the highest doping levels displayed the strongest IR emission intensity. These infrared CL bands were also observed in the GaN:Mn codeloped with Si, but not in the nominally undoped sample, suggesting that their origin is related to deep donors/interstitial structural defects. The red absorption shoulder rather than to the charge transfer processes involving the Mn3+ acceptor itself.

9:45 AM Y8.6
Magnetic Properties of Mn-doped GaN, InGaN, and AlGaN. Meredith L Reed,1 E. Acton Berkman,2 Mason J Reid,1 P. Erdem Arkun,2 Sahil M Bedair3 John M Zuev3 and Nadia A El-Maaray3.1Electrical and Computer Engineering, National Research Council and North Carolina State University, Raleigh, North Carolina; 2Department of Materials Science and Engineering, North Carolina State University, Raleigh, North Carolina; 3Department of Electrical and Computer Engineering, North Carolina State University, Raleigh, North Carolina; Army Research Office, Research Triangle Park, North Carolina.

We report on the growth and magnetic properties of single crystal Mn-doped GaN, InGaN, and AlGaN films. The GaN:Mn films were grown by metal-organic chemical vapor deposition, while the Mn doping was performed by solid-state diffusion of a surface Mn layer deposited by pulsed laser ablation. Mn-doped In0.53Ga0.47N films were grown with x ≤ 0.15, where the easy axis of magnetization depends on the stress state of the In0.53Ga0.47N film. The easy axis rotates from in-plane to out of plane by changing the film thickness thus going from strained to fully relaxed films. Mn-doped Al0.20Ga0.80N films were grown with x < 0.40 showing ferromagnetic behavior above room temperature. Temperature dependent superconducting quantum interference device measurements confirmed the absence of superparamagnetism within the films. By optimizing the growth and nominally undoped conditions of III-Nitride dopant growth, Hall Curves in the temperature range of 292 to 500K. These Mn-doped III-Nitride films have ferromagnetic behavior with hysteresis curves showing a coercity of 1000 Oe. Transmission electron microscopy confirmed the absence of any secondary phases within the films used in this study. Hall Effect measurements showed that magnetic properties exist in both insulating and n-type films.

10:30 AM Y8.7

Atomic configurations corresponding to local-energy minima for an isolated O atom in wurtzite GaN are identified using density-functional theory and the generalized-gradient approximation for exchange and correlation. Formation energies computed for these
Configuration as a function of the charge state are used to estimate defect energy levels in the gap and to predict the dominant O configuration. The formation of Fermi level pinning, and DX configurations are examined and the interaction of H with these configurations is explored. Energy barriers are also reported for O migration through the lattice. This work was partially supported by the U.S. Dept. of Energy. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the U.S. Dept. of Energy under Contract DE-AC04-94AL85000.

11:30 AM Y8.10
Hydrogen Release and Isotope Exchange by p-GaIn in Vacuum, N2, O2, and H2: Experiment and Theory.
Shawn O'Myers, Bastian I. Vanstrijk, Carolly He Senger, and William R. Wampler; Sandia National Laboratories, Albuquerque, New Mexico.

The results and isotope exchange of H by p-type GaIn(Mg) during exposure to vacuum, N2, O2, and H2 and has been measured and quantitatively described by a unified theoretical model. The result understanding bears on the optimization of acceptor-activation anneals in device processing. Using deuterium with nuclear-reaction analysis permitted release isomers to be followed over two decades in bulk concentration, facilitating the determination of kinetics. Surface accumulation of oxygen was quantified by employing O-18 with nuclear-reaction analysis. IR spectroscopy of the Mg-H complex probed the concentrations of both proton and deuterium during isotope exchange. All results are quantitatively consistent with a model whereby H in bulk solution equilibrates rapidly with a small population in surface sites, so that adsorption and description limit the movement of H to and from solution. In high vacuum and UHV, the description is predominantly by H-H recombination and is second-order in H surface coverage, as previously reported by us. Leakage by vacuum isothermally additively reveal an emerging first-order H-desorption process, provisionally attributed to the release of N-H species. N2 at atmospheric pressure increases the first-order recombination by several times, possibly through an enhanced density of reactive surface N. O2 isotherms manifest the surface recombination rate at the parallel rate in the torr range. O2 isomers indicate first-order H description initially, consistent with the release of O-H species. The results then slowly alters, converging with the buildup of O as expected for oxide-blocking. Isotope exchange between solution and external H2 gs is orders of magnitude faster than release into vacuum, confirming H-H recombination as the dominant rate-determining step in release. 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 US DOE under Contract DE-AC04-94AL85000.

11:45 AM Y8.11
Mg Doped GaN Using A Valved, Thermally Energetic Source: Enhanced Incorporation, Control and Quantitative Optimization.
Shawn O'Myers1; G. Namkoong2; W. A. Doolittle3; and A. S. Brown4;1Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, Georgia; 2Duke University, Durham, North Carolina.

P-type GaN has traditionally been grown by molecular beam epitaxy (MBE) with Mg as the dopant, using an effusion cell with the flux a function of the cell temperature. However, due to the high vapor pressure of Mg, it is difficult to control the flux below the equilibrium concentration alone. Given the small sticking coefficient and surface accumulation issues related to Mg doped GaN, it may be beneficial to have a more reactive species of Mg impinging on the sample surface. Unfortunately, with conventional electron beams, the flux and flux energy are coupled together through the cell temperature. It would be ideal to control the flux separate from the flux energy, as well as attenuate the flux independently of the cell temperature with a valve control. In this study, a thermally energetic Mg source with a variable flux control is used to vary the Mg concentration in GaN. Mg flux is varied, retaining a constant thermal energy, from 1e10 Torr beam equivalence pressure (BEP) to well above the saturation limit1 [8e-10 Torr BEP] in steps separated by undoped GaN. The effects of the thermal energy of the Mg flux on Mg incorporation, two Mg temperatures were investigated: one well above the melting point of Mg (980°C) and one slightly below the melting point of Mg (900°C). Results were analyzed using secondary ion mass spectrometry (SIMS). For a constant BEP, the incorporated Mg increased by greater than ten times when the Mg thermal source temperature was raised from 925°C to 980°C. During SIMS analysis, the energy spectra of sputtered Mg was determined. The data below the critical flux for saturation, possibly providing a quantitative means of optimizing p-type conduction. This effect may be related to a change in sample charge incurred from a transition insulating to conducting layers. G. Namkoong1; W. A. Doolittle, and A. S. Brown, Applied Physics Letters 77, 4386 (2000).
SESSION V: Characterization II  
Chair: Nadin ELMasy  
Thursday Afternoon: December 4, 2003  
Room 312 (Hyenas)

1:30 PM Y9.1  
High optical efficiency GaN layers on O and Zn face ZnO.  
Xing Gu, Xiaoxin Xiu, Michael Reschikov, Lei He, Feng Yan, Daniel Johnstone, Jeff Nause, and Hidai Morikawa.  
Electrical Engineering, Virginia Commonwealth University, Richmond, Virginia;  
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ZnO is a highly efficient photon emitter, has optical and piezoelectric properties that are attractive for a variety of applications. Due to its stacking order it is intrinsic to GaN is also considered as a substrate material for GaN epitaxy. In the past the poor preparation of ZnO surface has been a major hindrance to GaN epitaxy. However, a treatment we developed renders both O and Zn faces of ZnO smooth with atomic terrace. Epitaxy of GaN on O-face and Zn face of ZnO by reactive molecular beam epitaxy was performed. We used low-temperature RF growth of GaN buffer layer on ZnO surface to protect it from both ammonia and Ga. No Ga2ZnO4, an oxide with the spinel structure, formed due to reaction of ZnO with Ga, was found, in contrast to earlier reports. The low-temperature photoluminescence (PL) indicates that both faces of ZnO lead to GaN with high radiative efficiency. In the previous research it has been reported that O-face ZnO is slightly better for GaN epitaxy. Our new finding demonstrates that high-quality GaN epilayers can be grown on Zn face of ZnO as well indicating the efficacy of the surface treatment. In particular, contribution of the donor-acceptor-pair PL band in GaN on ZnO is about the same that on GaN on Si, while growth on ZnO shows very low levels of defects, of them are in pretty low level compared with the exciton peak. This can be attributed to a reduced background doping into GaN from Zn-face ZnO compared with O-face ZnO.

1:45 PM Y9.2  
Structural and optical characterization of (InGa)N layers grown by MBE.  
Pierre Ritterman, Prostina Singh, Jochen Aderhold, Jürgen Greffet, and Valeriano Sorescu.  
LIPMAT, ENSICAEN, Caen, France;  
University of Hannover, LIT, Hannover, Germany;  
LOFFE, St Petersburg, Russian Federation.

Nitride semiconductors [AlN, GaN, InN and their alloys] have great potential for use in optical devices and high-power, high-frequency electronic devices. Among these nitrides, InN has the smallest effective mass and the highest electron drift velocity. Which set it as a very promising material for the channel layers in high-speed and high-frequency electronic devices. However, difficulties in growing high quality InN films have hindered the understanding of the properties of InN and their applications. During the past few years, the development of growth techniques, especially in molecular beam epitaxy (MBE), have significantly improved the quality of InN films attaining Hall mobility beyond 2100 cm2/Vs and carrier concentration close to 3*1017/cm3 at room temperature. In these high quality InN films, a narrow bandgap (<0.7 eV) has been reported. However structural properties of InN films such as defects, interface, crystallinity, polarity etc. have been studied rather poorly. In this work, we investigate the microstructure, defects and growth modes of (In, Ga)N films grown by MBE using transmission electron microscopy (TEM). Thick ternary films were successively grown for a indium fraction varied from 6% to 100%, we analyze the evolution of the layer structure versus the indium composition. We correlate the results of surface roughness analysis by AFM to the TEM measurements of the surface morphology. The overall crystal state is investigated also by XRD and correlated to TEM imaging and diffraction for a complete determination of the nature of the defects inside the layers and their distribution versus the In composition. PL measurement allow us to follow the evolution of the band gap energy.

2:00 PM Y9.3  
The Structure of Dislocations in GaN Grown by MBE as a Function of the Gallium to Nitrogen Ratio.  
Marcus Q. Baines 1, David Cherns 1 and C Thomas Foxon 2.  
1 H H Wills Physics Laboratory, University of Bristol, Bristol, United Kingdom;  
2 Dept Physics and Astronomy, University of Nottingham, Nottingham, United Kingdom.

Determining the core structure and surroundings of dislocations is of great interest in understanding their electrical properties. In previous work [Baines et al, Mat. Res. Soc. Symp. Proc. Vol. 743 I.2.5. (2003)] we showed that dislocations grown under open core dislocations, whereas dislocations in GaInN samples were closed-core. In this work we investigate samples grown with a range of Ga pressures by molecular beam epitaxy (MBE) on GaN templates on sapphire substrates. The surface morphology was studied by atomic force microscopy (AFM). This showed that in samples grown under Ga-rich conditions surfaces were generally smooth but with a few well-defined and pronounced pits. In contrast, samples grown under Ga-poor conditions were much rougher on a fine scale. Transmission electron microscopy (TEM) images taken on plan view samples were in good agreement with the AFM results. These studies showed that the pits observed in Ga-rich samples extended into the foil, and were generally not always associated with threading dislocations.

2:15 PM Y9.4  
Atomic Scale Characterization of Impurity Segregation and Electronic Structure Changes at Dislocations in GaN.  
Ilie Arslan 1, Sebastien Ozou 2 and Nigel D Browning.  
1 Physics, University of California-Davis, Davis, California;  
2 Chemical Eng. & Math Science, University of California-Davis, Davis, California;  
3 National Center for Electron Microscopy, Lawrence Berkeley National Lab, Berkeley, California.

Despite an intense research effort for more than a decade, the fundamental role of impurity segregation at dislocations in GaN is still the subject of strong debate. Although GaN-based light emitting diodes (LEDs) and lasers are currently being developed, device failure at the dislocation is the principal cause of continued research into the relationship between structural and properties of threading dislocations. Furthermore, impurity segregation to dislocation cores is an important and understood surface area, particularly for present and future applications such as LEDs. To study these effects, a detailed atomic scale characterization of the structure and electronic properties has been performed experimentally using the simultaneous resolution Z-contrast imaging and electron energy loss spectroscopy (EELS) techniques in a scanning transmission electron microscope (STEM), and theoretically using density functional theory (DFT) calculations. Previous simulations indicated that intrinsically there are no states formed in the band gap, and hence stoichiometric core are not responsible for electrical activity. With these simulations as a basis, atomic resolution experiments were performed on three variants of screw dislocation: the full core, the partially filled core, and the full core oxygen. Oxygen was found to be present at the edges of the core, having the strongest concentration at the surface layers, but continuing for approximately 20 monolayers into the sample. The partially filled core had a weaker, but measurable oxygen signal, and the full core was not found to contain oxygen within the detection limits. These oxygen impurities create states in the band gap, and hence appear to be the origin of the unwanted electrical activity at the core. The results suggest that this electrical behavior is primarily driven from the open and partially filled cores, which are much less prevalent than the filled cores, and may explain the initial insensitivity of GaN devices to the high density of threading dislocations.

2:30 PM Y9.5  
Microstructure of Thick InGaN Epitaxial Layers.  
Lijun Gong 1, Sridhar Srinivasan 2, Ron Liu 3, Bin Jiang 3, Hiroshi Omiya 1, Fernando A. Perez 1, Shintaro Tsunakawa 4, and Yoshinori Nakagawa 4.  
1Physics and Astronomy, Arizona State University, Tempe, Arizona;  
2Nokia Corporation, Ann Arbor, Michigan;  
3Tokushima, Japan.

In GaN quantum wells used in the active region of light emitting diodes are usually grown under conditions far from equilibrium. Their microstructural properties are not well understood due to the fact that the layers are severely strained and exhibit strong piezoelectric fields, and to the lack of information about bulk properties of these alloys. Knowledge of the microstructure of InGaN thick layers is limited at the present time due to the difficulty in growing high-quality thick films. In this study we have studied the microstructure of 100 nm thick InGaN films using TEM. The layers were grown on GaN on sapphire substrates with In compositions ranging from 0.03 to 0.22 as determined by Rutherford backscattering spectroscopy. We observe significant changes in the microstructure as the indium composition is varied. Samples with high indium composition (e.g., InGaN > 0.2) have a high degree of homogeneous matrix with isolated indium-rich regions in the vicinity of pits at the termination of threading dislocations. For compositions above 0.17, there is a breakdown in the crystalline structure and the layer is poly-crystalline in nature. Our observations of microstructure closely follow solid phase miscibility calculations for InGaN published in the literature. This study gives a fundamental understanding of the nature of these materials and could be useful in solving key issues.
associated with the growth of high-quality InGaN.

2:45 PM Y9.6
Dislocation Propagation and Strain Relaxation in GaN Films on Porous SIC, Ashutosh Sagar 1, Randall M Feiststra 1, C. K. Inoki 1, T. S. Kuan 1, F. Yun 1 and H. Morikou 1, 2, 3, 4 (Carnegie Mellon University, Pittsburgh, Pennsylvania) 1, 2, 4 (Physics, Carnegie Mellon University, Pittsburgh, Pennsylvania) 1, 2, 4 (Physics, University of Alabama at Birmingham, Birmingham, Alabama) 1, 2, 4 (Electrical and Computer Engineering, Virginia Commonwealth University, Richmond, Virginia)

We have grown GaN on porous SIC substrates and studied the effect of substrate porosity on the overgrown film quality in terms of defect structure and film strain. The growth was performed by both plasma-assisted molecular beam epitaxy and reactive molecular beam epitaxy. The GaN growth was performed using carrier-free trimethylgallium with a CoSi source in addition to the usual in situ hydrogenation. Transmission electron microscopy (TEM) and x-ray curvature measurements by surface profilometry. TEM images show that the GaN film grown on porous substrates contains open tubes and a relatively low density of threading dislocations. GaN grown on GaN films were grown to cover a substrate temperature range and a GaN flux ratio range that spans from the N stable to the Ga droplet regimes. Both samples. Identical growth templates were used to evaluate the effect of stress in dislocations between samples so that plan defect variations could be tracked. For all samples, traps are detected at E_g = 0.25, 0.60, 0.90, 1.35, 2.40, and 3.28 eV. The new valence bands at E_g = 3.04 and E_g = 3.28 eV are found to be strongly dependent on GaN flux with decreased concentrations as a function of increasing Ga flux toward the Ga droplet regime, with little change in concentration of the E_g = 2.40 eV level that has been attributed to V_n, a difficult to quantify, but no strong correlation with growth parameters is observed over the range studied. The dependence for defects is more complex, with growth temperature and GaN flux ratio suggest different physical point defect sources, which will be discussed in detail in the context of growth conditions and the growth phase diagram.

3:30 PM Y9.7
Atomic Structure of Defects in GaN:Mg: Influence of Annealing, Jaana Lehto-Lamminen 1, Tommy Tommervik 1, Dmitri Zakharov 1, Jaakko Jussila 1, Michael O’Keefe 1 and Kimmo Sarntinen 1, 2, 3 (Materials Science Division, Lawrence Berkeley National Laboratory, Berkeley, California) 1, 3 (Helsinki University of Technology, Espoo, Finland)

A direct reconstruction of the plane and amplitude of the scattered electron wave from a focal series of high-resolution images was applied to determine the atomic structure of defects detected in GaN:Mg films grown from diluted solution of atomic nitrogen in the liquid gallium at high pressure and also in crystals grown by MOCVD method. Crystals grown with Ga-polarity were studied. The majority of defects appear as a three-dimensional Mg-rich pyramids with their base on the (0001) plane and six walls which, on average, can be described as [11-20] planes. Detailed high-resolution study shows formation of facets or the formation of dome shaped figures on the side walls. Some of these defects appear in cross-section as rectangular defects. These defects are terminated by c-planes. Such defects can be parts of pyramids in thin TEM foils or can be formed from large clusters of Mg accumulated on the c-plane. These two shapes of defects observed in cross-section can be distinguished in the same crystals. The density of pyramidal defects depends on Mg concentration but their distribution within the crystal is not always uniform. Formation of new pyramidal defects can be observed upon annealing. Correlation of these results with photoluminescence studies performed on the same crystals will be presented. The mechanism of formation of these defects is rather complex. Very often the thickness within the defects is smaller than surrounding matrix, and some of them have empty holes within them. Our recent high-resolution images, which allow one to distinguish between Ga and N atoms, showed that some of these defects are inversion domains and others are not. It will be shown that these inversion areas are close to the pyramidal walls but the center of the defects can be empty or show slightly modified composition. Since growth rate with N-polarity is slower than growth with Ga-polarity (characteristic for the matrix), it is not surprising that some empty areas can be found within these defects. Formation of empty holes in GaN was also confirmed by positron annihilation study. The models of the inversion initiated from the side walls and reversing the polarity on the base of the defect, which allows further growth with the matrix polarity, will be presented.

4:00 PM Y9.8
Influence of Growth Parameters on the Deep Level Spectrum in MBE-Grown n-GaN, Aaron Arehart 1, 2, 3, 4, P. Colobrzeg 1, B. Heying 1, 2, J. S. Speck 1, U. K. Mishra 1, S. P. DenBaars 1, 2 and S. A. Ringel 1, 2 (Department of Electrical Engineering, The Ohio State University, Columbus, Ohio) 1, 2 (Materials and Electrical and Computer Engineering Departments, University of California, Santa Barbara, California)

The impact of growth temperature and GaN flux ratio on deep levels in GaN grown by molecular beam epitaxy (MBE) is systematically investigated using both deep level optical spectroscopy (DLOS) and deep level transient spectroscopy (DLTS) in a study designed to map the presence and concentration of defects over a defined region of the growth. A series of six different growth conditions were grown to cover a substrate temperature range and a GaN flux ratio range that spans from the N stable to the Ga droplet regimes on both samples. Identical growth templates were used to eliminate variations in dislocations between samples so that point defect variations could be tracked. For all samples, traps are detected at E_g = 0.25, 0.60, 0.90, 1.35, 2.40, and 3.28 eV. The new valence bands at E_g = 3.04 and E_g = 3.28 eV are found to be strongly dependent on GaN flux with decreased concentrations as a function of increasing Ga flux toward the Ga droplet regime, with little change in concentration of the E_g = 2.40 eV level that has been attributed to V_n, a difficult to quantify, but no strong correlation with growth parameters is observed over the range studied. The dependence for defects is more complex, with growth temperature and GaN flux ratio suggest different physical point defect sources, which will be discussed in detail in the context of growth conditions and the growth phase diagram.
Strain distribution in GaN/Si(111) epilayers with inserted SiN, A.J. Hilkens1, U. Hübner1, C. Thomsen1, T. Riemann1, F. Bertram2, J. Christen2, A. Dodgen3 and A. Krosgaard3; 1Inst. f. Festkörperphysik, TU Berlin, Berlin, Germany; 2Institut für Experimentelle Physik, Otto-von-Guericke Universität, Magdeburg, Magdeburg, Germany.

Control of strain distribution and eliminating of crack formation is essential for the growth of high quality GaN/Si epilayers. The lattice mismatch between these two materials and substrates is particularly different. Therefore, thermal expansion coefficients are origin of tremendous tensile stress. The use of low-temperature AlN [1] combined with ultrathin Si interlayers [2] is a promising design method to overcome these problems [3, 4]. To investigate their impact on the structural and optical properties series of GaN/AlN(111) samples with different interlayer design growth by metalorganic chemical vapor deposition (MOCVD) were investigated using micro-Raman spectroscopy and cathodoluminescence microscopy (CL). Samples with identical growth sequences but consecutively increasing deposition step of the final GaN layer enable a systematic analysis of the strain evolution step by step. The Raman spectra in the vicinity of the E2(high) mode are a common powerful tool for probing the strain distribution. The final growth procedure starts with isolated GaN islands on the SiN, which are almost stress free. With increasing concomitant tensile stress evolves and increases with GaN layer thickness. The micro-Raman results are in perfect agreement with our found stress-free tensile stress of the thicker GaN layers we found no indication for cracks. Moreover, no impurity incorporation, which would result in high local carrier concentration are found in the Raman spectra. Changing the sample design by inserting a GaN/N/AlN prior to the deposition of the SiN interlayer results in two E2(high) peaks in the spectra: one originating from the compressively strained template and the other from tensile strained final GaN film. The dependence of the GaN domain geometry on the SiN interlayer thickness is quantitatively evaluated.

**Y10.2**

**Modulation Doping of AlGaN for Improved Deep UV LEDs**

Jianying Zhang, Hongmei Wang, Zheng Gong, Ming Su, Shuai Wu, Hongbo Chen, Zhibao Liu, Wei Jin, Min Chen, Weining Ren, Guorong Yang, Qinlan Shi, M. Afsar Khan; EE, Univ. SC, Columbus, South Carolina.

At present the key performance limiter for state-of-the-art deep ultraviolet light-emitting diodes (UV LEDs) is the relatively poor material quality and the doping efficiency of the n- and p-type AlGaN. In the past we have utilized AlN/AlGaN superlattices and pulsed atomic layer epitaxy (PALE) grown high-quality AlN buffers to improve the structural quality and reduce the defects in such AlGaN layers. We now report a study of n- and p-type modulation doping of high-Al-content AlGaN layers for deep UV LEDs. Two modulation doping layers, a delta (d) doping where monolayers of the SiMg doped were inserted in the bulk AlGaN layers, and the second, where modulation doped (Si)Mg AlN/AlGaN multiple layers were used. The 5d doping was found to be very effective in reducing the etch damage (threeding dislocations). For an 10.5Ga0.5N layer the etch pit density reduced to 108 cm-2 from the starting value of over 109 cm-2. However, the superlattices modulation doped (Si)AIN/AlGaN 5N layers exhibited the highest Hall mobility and structural quality as measured by the symmetric/asymmetric scans of high-resolution x-ray diffraction (XRD). At a doping level higher than 1018 cm-3, the (Si)AIN/AlGaN 5N layer had a room-temperature Hall mobility of 320 cm²/Vs, full width at half maximum (FWHM) values of 2.7 and 5.8 arcmin for the XRD (102) and (114) rocking curves, respectively. Our new modulation-doping scheme also results in enhancement of crystal perfection in p-type AlGaN layers with Al-content up to 30%. For an AlGaN 5N layer we measured a room temperature hole concentration of 1.1e17 cm-3 and a mobility of 8 cm²/Vs. We will discuss the growth, and electrical and optical characteristics. Improvement in the deep UV LED performance from the use of modulation-doping schemes will also be presented.
fraction. An alternative approach is to employ an electron-beam as an excitation source. Electron-beam pumped blue lasers based on InGaN MQW structures show lasing at threshold pump power of 300-500 kW/cm², with a factor of 3.5 higher than typically achieved in InGaN MQW violet optically pumped case. Apart from a well-defined threshold, the lasing was characterized by narrow linewidths of well edges of edge emission at 2.7 mm with well defined (no. 0.1 nm linewidth) cavity modes present, as we all as more than 100-1 cavity modes present.

Y10.5 Emission Mechanisms in UV Emitting GaN/AlN Multiple Quantum Well Structures. Madiha Bura³, Alexander N. Cartwright¹, Hong Wa² and William J. Schiff². ¹Electrical Engineering, University of Buffalo, Buffalo, New York; ²Electrical Engineering, Cornell University, Ithaca, New York.

The need for efficient UV emitting semiconductor sources has prompted the study of a number of heterostructures of III-N materials. In this work, the temperature dependence of the photoemission (PL) properties of UV-emitting GaN/AlN multiple quantum well (MQW) heterostructures were investigated in detail. In all samples studied, the structure consisted of 20 GaN quantum wells, with well widths varying between 7 and 15 Ångstrom, clad by thin AlN barriers. The samples were processed by direct wafer bonding that was demonstrated on sapphire by molecular beam epitaxy. The observed energy corresponding to the peak of the emission spectrum is in agreement with a model that includes the strong confinement present in these structures and the existence of the large bulk-inegrated electric field and spontaneous polarization present inside the wells. The observed emission varies from 3.5 eV [15 Ångstrom well] to 4 eV [7 Ångstrom well]. Two activation energies associated with the photoemission intensity decrease in the well temperature dependence from the full width at half maximum (FWHM) of the PL feature indicates that inhomogeneous broadening dominates the spectrum at all temperatures. For the 15 and 13 Ångstrom wells, we estimate that the electron-hole interaction is responsible for less than 30% of the broadening at room temperature. This broadening is negligible in the 9 Ångstrom wells over the entire temperature range studied.

Moreover, well width fluctuations are primarily responsible for the inhomogeneous broadening, estimated to be of the order of 25 meV for half-a-monolayer fluctuation in well width.
Y10.9 Persistent photocurrent in GaN Schottky ultraviolet detectors, Odil Kurz, God Balir and Joseph Salzman; Electrical Eng., Technion, Haifa, Israel.

GaN based Schottky detectors provide high response and low noise at UV wavelengths. Although typical photovoltaic sensors should ideally not exhibit gain, the presence of gain has been reported in many research works [42,43,44] and a model for it was proposed by J. W. McCreary and M. C. Ferraro [45]. We present a microscopic model to explain this temporal behavior. We have implemented GaN based Schottky detectors and measured their photocurrent response as a function of the incident power, and the measured photocurrent show gain saturation and PPC behavior as depicted above. We present a microscopic model of the gain mechanism to explain these observations. Further, we extract physical properties, such as trap density at the semiconductor-metal interface and their trapping lifetime, from our measurements. Finally, we connect the fitting parameters of the stretch-exponential, to the device physical properties. J. W. McCreary, V. G. Meyer, G. Balir, and J. Salzman, Appl. Phys. Lett. 80 (3), 347 (2002) 2. E. Monroy, F. Calla, E. Munoz, and F. Omnes, Appl. Phys. Lett. 72 (22), 3401 (1998) 3. D. Wheller, E. Monroy, P. Kung, J. Wu, M. Hamilton, R. Przybylo, M. S. Dyer, and M. R. Quay, Appl. Phys. Lett. 72 (8), 592 (1998) 4. O. Kuz, V. G. Ganz, M. G. N. Balir, and J. Salzman, Appl. Phys. Lett., 79 (10), 1417 (2001) 5. J. C. Carrano, T. Li, P. A. Grudowski, J. C. Ernst, R.D. Dupuis, and J. C. Campbell, J. Appl. Phys. 83 (11), 6148 (1998)

Y10.10 Design and fabrication of GaN-based light-emitting diodes with enhanced light extraction. Hyunsoo Kim, Jeelhee Cho, Hye Jeong Oh, Jeong Wook Lee, Sahlo Yoon, Cheolho Song and Yongjo Park; Samsung Advanced Institute of Technology, Yongin, Gyeonggido, South Korea.

We have designed and fabricated GaN-based light-emitting diodes (LEDs) with enhanced light extraction efficiency. For the efficient light extraction from the LED chip, it is more desirable to extract the traveling light toward lateral direction since the light of the lateral portion is maximally reduced. We extracted the extraction ratio of light of the lateral portion is maximally reduced. In this regard, we designed LED chip with a number of holes acting as lateral exits for light extraction. These holes were fabricated from fine patterning by conventional photolithographic technique and selective etching process. It was interesting to note that the etching depth played an important role in changing the extraction efficiency. This could be explained by relationships between the critical angle (law of Snell) and lateral device geometry. Based on the optimized design, the LED chip showed the improved light output efficiency by 25%.

Y10.11 Reduction of dark current in AlGaN/GaN Schottky barrier photodetectors with a low-temperature-grown GaN cap layer. Gao-Chung Chi,a Jim-Jong Shiu,a Min-Lunm Lee,a Yen-Kuin Su,a Shou-Jin Chang,a Wei-Chi Lia,b and Wen-Jen Lin;b 1Department of Physics, National Central University, Chung-Li, Taiwan; 2Institute of Microelectronics Engineering and Research, National ChongKung University, Tainan; 3Materials & Electro-Optic Research Division, CHUNG-SHAN INSTITUTE OF SCIENCE & TECHNOLOGY, Lung-Tan, Ta-Yu-nan.

AlGaN-x is one of the most promising materials for the fabrication of high-sensitivity visible-blind ultraviolet (UV) detectors, since it has a large direct band gap (2.9 eV at 300 K). Recently, the results show that the latter requires precise control over surface and interface changes, which are intimately related to the strong piezoelectric and spontaneous polarization fields present in the wurtzite nitrides. We have studied nitride heterostructures and their surface and interface properties using x-ray diffraction and electron stimulated desorption in an ultrahigh vacuum system. Our samples were...
InN/GaN (801) superlattices with one invariant atomic substitution layer can be regarded as perfectly InGaN ordered alloys. Owing to their efficient optical excitonic transitions, the extreme case of atomic substitution layers in the active region is expected to play a crucial role for the next generation optical devices. In this paper, we show how a modification of InGaN quantum wells on the chemical and size effects associated with the embedded InN substitution layer. Using a first-principles method, we investigate the electronic and optical properties of a two-dimensional InN substitution layer embedded in GaN. The present calculations are based on “state-of-the-art” DFT-LDA using the selfconsistent full potential linear augmented plane wave method within the local-density functional approximation. The InGaN alloy is known to be an “alloy” alloy because large composition-dependent band gap coefficients and new defect levels appearing in the band gap of GaN have been observed experimentally. We will show theoretically that InN/GaN shows some band structure anomalies in the lower conduction band region.

Y.10.18

Substrate effect on aging for AlGaN/GaN HFET outpagers grown by MOCVD. Ronald Berkhemer, David W. Gottschall, Shijing Guo, Brian Albert, Dovo Caucas, Dong Lu and Boris Peres; Corporate R&D, Emcore, Somerset, New Jersey. AlGaN/GaN heterostructure field effect transistors (HFETs) are envisioned for use in a range of high power, high frequency amplifier applications. Concurrent to improvements in the materials properties and device designs for these AlGaN HFETs, reliability of the packaged amplifiers is being investigated to establish the limits of these materials system to achieve smoother interfaces, higher Al compositions, and thicker barriers. Until recently, all the reliability research has been on devices, but recent work at Emcore has revealed significant long term aging effects that occur in the GaN/epitaxial material stack as well as within the previous heterojunctions. At the p-n junctions, the p-n GaN rectifiers show the advantages of employing a GaN substrate to make a true vertical transport geometry device. These devices appear very promising for high power switching applications.

Y.10.19

X-ray Diffraction Analysis of Threading-Dislocation Density in GaN-Based HEMTs. Allen West1,2, Stephen Lee1, Andrew Allison1, Karen Wadrip1, David Follstaedt1 and Cammy Athernaby1; 1Sandia National Laboratories, Albuquerque, New Mexico, 2Materials Science and Engineering, University of Florida, Gainesville, Florida. The device performance of GaN-based HEMTs is limited by the high threading-dislocation density associated with GaN film grown heteroepitaxially on SiC. Threading-dislocations in the GaN limit mobility by scattering electrons in the HEMT conductive channel. In this study, we develop improved x-ray diffraction (XRD) methods for measuring the threading-dislocation density in GaN we then apply these methods to the analysis of GaN-based HEMTs. The XRD analysis measures the characteristic width for a series of GaN Bragg peaks. Symmetric (0002), (0004), and (0006) reflections, as well as asymmetric (1k11) and (2004) reflections. The lattice parameter, the twist variance, and the lateral coherence length of the GaN epilayer are extracted from the measured peak widths using a reciprocal-space model that describes the (k1) dependence of the corrected peak width with curvature. The tilt variance, the twist variance, and the lateral coherence length of the GaN epilayer are then estimated from the XRD measurements of tilt, twist, and coherence length using two separate methods. The first method proceeds using the tilt and twist variances and the classic formulation of the X-ray method proposed by Taylor and Koch. The second method assumes that the measured coherence length equals the rms spacing of randomly arranged threading dislocations, a very strong assumption. For selected samples, the threading-dislocation density determined by XRD is benchmarked against transmission electron microscopy, good agreement is found. The validated XRD
Recently we reported the first AlGaN/GaN heterojunction bipolar transistor (HBT), a device that might combine the high-breakdown voltage of an n-GaN collector with the high mobility of an AlGaN/GaN emitter-base. [1] Because the high degree of lattice mismatch between GaN (lattice constant of 5.05\(\text{\text{\AA}}\)) and GaN (3.19\(\text{\text{\AA}}\)) precludes an epitaxial formation of this device, we formed the GaN/GaN heterojunction via wafer fusion, also called direct wafer bonding. The conduction band offset of the wafer-fused GaN-GaN heterojunction is unknown. However, a positive offset is likely, given the electrical characteristics and low current gain observed in our previous work. A positive conduction band offset due to factor-induced traps or defects, or to the natural conduction band offset between GaN and GaN regardless of the fusion process. This new HBT is being modified to a more likely conduction band spike. Our new HBT structures have reduced base thickness of 1.0 nm and an n-GaN base-collector setback layer of two different thicknesses (20 or 50 nm). A setback layer should shift the band gap of GaN closer to that of the collector. By decreasing the barrier in the conduction band at the base-collector junction, these new structures may increase collector current and hence current gain. Gummel plots and common-emitter I-V characteristics will be presented. Additionally, simulated energy band diagrams suggest alternative improvements for the HBT material. Possibilities include the addition of a Si delta-doped layer at the collector side of the junction, the use of a highly doped GaN (rather than the base-collector setback material such as AlGaN). References: [1] S. Estrada, Hui Xing, Andrea Stoner, Andrew Huntington, Umesh Mishra, Steven DenBaars, Larry Coldren, and Evelyn Hu, Applied Physics Letters 82 (5), 826-8 (2003) [2]. Accepted for publication: Sarah Estrada, Andrew Huntington, Andrea Stoner, Hui Xing, Umesh Mishra, Steven DenBaars, Larry Coldren, Evelyn Hu, Applied Physics Letters 83 (3), (tentatively scheduled July 21, 2003). Further information: S. Estrada, http://srh8.optimism.ucsb.edu/ http://srh8.optimism.ucsb.edu/
passivation, the device shows small current dispersion (< 10%) under 1 μs pulse gate driving.

Y.10.24
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A custom-built multi-wafer metalorganic chemical vapor deposition reactor has been developed for the optimal growth of AlGaN/GaN-based high electron mobility (HEMT) structures on silicon substrates. Gas flow modeling and flow back monitoring techniques were used to develop the reactor design to minimize composition and thickness variability of deposited films. Real-time in-situ chemical sensing of precursors, additives, and byproducts was used to optimize the quality of AlN, GaN, and AlGaN films and to ensure reproducibility of the deposition process. Multiple HEMT structures were grown on 4H- and 6H-SiC to establish the role of substrate and film properties as sources of HEMT performance variability. The structural, optical, and electrical properties of the substrate, modulation layer, and buffer layer were measured by several techniques, including x-ray diffraction (XRD), x-ray reflectivity (XRR), photoluminescence (PL), and Hall effect. Additionally, high-resolution maps of AlGaN composition and thickness were correlated to the measured properties of the substrate and films with HEMT performance metrics such as LMAX, fT, fmax, transconductance, output resistance, and breakdown voltage. It was found that the material properties best correlated with the electrical performance were substrate rocking curve linewidth, PL emission intensity, and AlGaN/GaN interface roughness (measured by XRR). While samples in this study showed differing defect microstructures and non-uniformity, current density values achieved in the AlGaN/GaN HEMT structures were 1.5 mA μm-2 with 2% Al content and 2.5 mA μm-2 with 22% Al content grown in a single wafer Aixtron reactor, on semi-insulating n+ 4H SiC substrates, using Triethylgallium (TEG), Trimethylaluminum (TMA), and ammonia (NH3) as group III and group V precursors. Critical impact of some growth parameters on the physical properties of the AlGaN/GaN epilayers, as identified in this work, includes: (1) SiC buffer surface preparation, (2) the AlGaN nucleation layer growth conditions (temperature, layer thickness, strain) appeared to be key steps of the AlGaN/GaN/SiC growth. AlGaN/GaN HEMT structures under study consisted of 3μm AlGaN n-/4μm GaN buffer layers followed by a 25nm S doped GaN layer with 2% Al content and an undoped GaN cap layer, 3μm thick. A specific design of the GaN buffer layer has been optimized in order to obtain insulating material. This was confirmed by a background doping lower than 10E14 cm-3 and a very low leakage current (10<sup>-1</sup> pA at 20V). The transport properties of such heterostructures were studied as a function of temperature from 300 K to 10K. Hall mobility higher than 1000cm<sup>2</sup>/Vs has been obtained for GaN epilayers with a sheet carrier density of 1.2×10<sup>13</sup> cm<sup>-2</sup>. The high mobility obtained at low temperature (300K/2V-1s<sup>-1</sup>) for the mentioned HEMT structures reveals a high quality of the GaN/GaN/SiC heterostructures, and which was confirmed at the atomic scale by TEM measurements. Other characterization techniques such as AFM, HR-XRD, C-V measurements and monochromatic have been applied to investigate the material properties of the GaN/GaN/SiC heterostructures. AFM and HR-XRD measurements evidenced a very good crystal quality of the GaN/GaN epilayers with a RMS close to 0.3nm, and a rocking curveFWHM of 10<sup>5</sup> lower than 80 arcsec related to the GaN layer. The device fabrication was performed using a conventional mean integrated process with RIE for metal deposition. Ti/Al/Ni/Au was used for ohmic contact formation and Pt/Au for the gate metal. The devices were realized with gate length of 1μm, 2μm and 4μm. The devices measured at 10GHz using a load pull system exhibit CW output power in excess of 28W/mm for a gate length of 2μm. Under static measurements we found a minimum drain current Idss around 1A/mm and a good pinch-off voltage of 4V.

Y.10.27
Microwave Growth of AlGaN/GaN HEMT Structures on 100μm Substrates.
David William Gothold, Brian Albert, Ronald Birckbank, Shiping Guo and Boris Peres. EMCORE, Somerset, New Jersey.

AlGaN/GaN High electron mobility transistors (HEMTs) have attracted a great deal of attention in recent years because of their promise for high performance RF devices and high temperature operation. A great deal of research has already been done on these devices using small (50μm) substrates. However, larger substrates are important due to both the high cost of processing wafers and the limited availability of narrow linewidth Lithography equipment needed for high performance devices. EMCORE is currently developing growth on 100μm thick AlGaN/GaN substrates in order to understand the issues involved in growth of large substrates and to speed the development of epitaxy on 100μm SiC onto such substrates become available. Because of the significant lattice and thermal mismatches on all substrates, as well as the extreme growth conditions used for GaN epitaxy, scaling wafer size is not as straightforward as in other compound semiconductor technologies. Wafer bowing, thermal variations, and strain all significantly affect uniformity, repeatability, and device performance. Using a variety of in-situ characterization tools, these effects can be studied and controlled through structure and process improvements. On these silicon substrates, AlGaN/GaN heterostructures have been grown with a sheet resistance of 360Ω/ and uniformity < 3% across the wafer.

Y.10.28
In-situ chemical sensing for real-time prediction of material quality and film thickness in GaN MOCVD.
Seon Chol, Gray W. Rubloff, Michael E. Aumer, Darren B. Thomas and Deborah P. Purdie.1 Department of Materials Science and Engineering and Institute for Systems Research, University of Maryland, College Park, Maryland.2 Advanced Materials and Semiconductor Device Technology Center, Northrop Grumman Corporation, Linthicum, MD.
Gallium nitride promises to be a key material for future semiconductor devices aimed at high frequency, high power electronic applications. Manufacturing for such high performance products will require systematic methods to achieve reproducible metrics such as material quality and film thicknesses in large structures. In a joint project between the University of Maryland and Northrop Grumman Corporation, we have undertaken this challenge and addressed it to accelerate learning at the R&D stage through the use of in-situ guided growth. Employed in this work is a real-time, in-situ, chemical sensing technique in the MOCVD process, real-time mass spectrometry reveals the generation of by-product species due to the deposition reaction as well as background impurity species in the process. By-product signals provide a real-time predictor of the crystalline quality of the material, as determined post-process by ex-situ XRD (x-ray diffraction), with the mass-spec/XRD correlation exhibiting an excellent sensitivity of 5% or less. Background impurity levels in the as-grown film were also closely correlated to post-process, ex-situ photoluminescence measurements for material quality. In addition, time-integration of the by-product signals through the deposition process cycle provides a thickness metrology suitable for controlling the thickness of the individual layers in the GaN-based HFET structure. These applications of real-time, in-situ chemical sensing, as predictors of material quality and film thicknesses, promise significant benefits in terms of reducing in R&D and advanced process control in GaN-based semiconductor manufacturing.

Y10.30 Growth of Bulk-like GaN Layers in a Vertical HVPE Reactor, Carl Hemmingsen, Henrik Larsson, Daniel Gogova and Bo Monnmand, IFM, materials science, Linkopings university, Linkoping, Sweden.

3 inch crack free GaN single crystal layers with a thickness up to 0.6 mm have been grown by hydride vapour phase epitaxy (HVPE) in a vertical hot-walled reactor at atmospheric pressure. The growth has been performed in a mixture of gallium chloride and ammonia at the temperature range 1050-1100°C with nitrogen as a carrier gas. The process gases are distributed from the bottom upwards through the reactor. Thus, the substrate is exposed downwards to the process gases. Using this reactor geometry, growth rates up to 350 µm/hr have been obtained. The growth process has been studied concerning the choice of template, pre-treatment and initial growth process. Several different substrates, both buffered and unbuffered, have been used in the investigation. The structural and optical properties of the layers have been studied using optical microscopy, X-ray diffraction (XRD) and low temperature photoluminescence (LTP). The result shows that the interface region between the template and the GaN single crystal layer and the uniformity of the layer thickness is important in order to obtain stress-released layers. Thus, in order to achieve crack free GaN layers of high crystalline quality an optimised reactor geometry, template pre-treatment, and initial growth process is necessary.


Cantilever epitaxy (CE) has been developed by our group to produce GaN on sapphire with low dislocation densities as needed for improved devices. A mechanism is employed to manipulate dislocations, which normally propagate vertically from the buffer layer to the surface, to turn them into the plane of the material. This technique has allowed us to achieve densities as low as 5 x 10^7/cm^2 averaged across multiple posts, overgrowth zones, and coalescence fronts on sapphire or other epitaxial substrates. As determined with AFM, TEM and cathodoluminescence (CL), this density is one to two orders of magnitude below that of conventional planar growths. These improvements suggest that large-area devices, such as LEDs, can be fabricated on these low defect density substrates. Recent work has been completed to eliminate a defect type seen in early cantilever epitaxy attempts, labeled as “dark-block defects” because they are non-radiative and appear as dark rectangles in CL images, and a repeatable method has been established for collecting large areas of cantilever epitaxy material without these defects. Characterization with SEM, AFM, and TEM of cantilever material in defect areas indicated that the structure is distinct between the two cantilever sections being brought together. Examination of the evolution of the cantilever films for many growths, both partial and complete will be presented and the importance of controlling the growth conditions and crystal morphology at multiple steps will be emphasized.

Y10.31 Abstract Withdrawn


The large defect densities associated with heteroepitaxial growth of group-III nitrides are detrimental particularly to laser diodes. Well-known lateral growth regimes such as epitaxial lateral overgrowth (ELOG) rely on overgrowth of pre-deposited nitride layers applied to dielectric masks. However, in order to avoid contaminations and simplify the processes it is advantageous to separate growth process and pattern formation. We have developed a patterning process for n-type doped SiC substrates based on photolithography (PEC) etching. Strip patterns aligned along either [1-100] or [1-10-2] directions, respectively, and periods between 5 and 10 microns were etched to depths between 0.5 and 2 microns. Low-pressure metal-organic vapor phase epitaxy (MOVPE) in a horizontal reactor was then used for overgrowth. We have previously shown that a defect reduction by this approach is possible and found an improvement by a factor of 5-10 compared to optimized growth on plane substrates. A further reduction requires more insight in the facet formation and stability. We performed growth experiments varying growth temperature, V/I ratio and total pressure. A defect reduction requires lower pressures compared to growth on plane substrates. For 50mbar and V/I ratios of 2500 lateral-to-vertical growth rates of more than 8 were found. A further reduction of pressure had no significant effect. We found instabilities for extreme V/I ratios of more than 5000. Here screw dislocation most likely originating at the substrate interface seems to be the cause. We find that in our growth environment facets of low angles between 18 and 30 degrees are surprisingly stable. We are presently investigating the nature of these facets which need to be avoided in order to efficiently reduce the density defect.

Y10.33 Migration Enhanced Metal Organic Chemical Vapor Deposition for IL-N Heterostructure Growth: Qalid Fadaih, Ramesh Gaind, Michael Shur, and Asif Khan, SENSOR Electronic Technology, Inc., Columbia, South Carolina, 2Department of ECSE and Broadband Center, Rensselaer Polytechnic Institute, Troy, New York; 3Department of EE, University of South Carolina, Columbia, South Carolina.

We report on a new Migration Enhanced Metal Organic Chemical Vapor Deposition (MEMO-CVD) epitaxial technique for growth of AlN/GaN/InN films and heterostructures. MEMO-CVD is an improved version of Pulsed Atomic Layer Epitaxy (PALE), which deposits quaternary AlInGaNx-yn layers by rephasing of units cell grown by sequential metal organic precursor pulses of Al-, In-, Ga- and N sources. In PALE, the duration of each pulse in the unit cell is fixed, and the NH3 pulse always followed each metalorganic pulse. In MEMO-CVD, the duration and waveforms of precursor pulses are optimized, and, generally speaking, the pulses overlap allowing for a continuous growth rate from PALE to MOCVD. MEMO-CVD combines a fairly high growth rate for buffer layers with reduced growth temperature (by more than 150C) and improved quality for active layers. Using this new technique, we were able to achieve a better mobility of pre-cursor species on the surface and, thus, better atomic incorporation and improved surface coverage. This enabled scale up of our epitaxial technology to four inch and allowed for precise growth of Strain and Energy Band Engineered structures resulting in elimination of aging effects in AlGaN/GaN heterostructures grown on large area substrates.


GaN thin films were grown via organometallic vapor phase epitaxy on 4H-SIC (1120) substrates using an AlN buffer layer. High resolution x-ray diffraction confirmed the GaN deposited epitaxially in the same orientation as the substrate. The misalignment was 1.8 degrees. The AFM images show that the microstructure of the AlN buffer layer and the subsequently deposited GaN have a highly oriented growth structure where parallel growth features propagate in the [1100] direction. No surface features were resolved using scanning electron microscopy imaging and the interfaces between the substrate, buffer layer, and epilayer were 654.
continuous. Plan-view transmission electron microscopy analysis showed stacking fault and threading dislocation densities to be \( \sim 1 \times 10^8 \text{cm}^{-2} \) and \( \sim 3 \times 10^7 \text{cm}^{-2} \), respectively.

Y10.35


One of the principle problems of high power electronic devices is the extraction of heat from the active region of the device. The thermal conductivity of the substrate is a crucial parameter affecting the thermal design of a good device. In this study we investigated the thermal conductivity at room temperature of 7 GaN and AlGaN/GaN layers grown on silicon, employing the 3 omega thermal conductivity method. By varying the thickness of the GaN layers from 0.2 to 7.5 nm, which indicates the thermal contact resistance between the GaN and Silicon substrate was shown to be very small. The thermal conductivity for the GaN layers was found to range from 130 to 140 W/mK which is comparable to thermal conductivity of the silicon substrate. In device quality films consisting of a 30nm AlGaN layer on GaN, the effective thermal conductivity of the Device layer was found to increase by about 10% to 150 W/mK. This result indicates that the heat transfer of GaN on silicon is as good as either GaN or silicon alone, and that no thermal degradation attributable to the GaN/Silicon interface is observed.

Y10.36

Growth of high quality crack-free GaN on AlN quantum dots over Si(111) substrates by MOCVD. Wenlong Sin1, Jingli Chen2, Linsuan Wang2 and S.J. Chun3; 1Optoelectronics and Photonics, IMRIS, Singapore, Singapore; 2Department of Materials Science, NUS, Singapore, Singapore.

Si as a substrate material for GaN growth promises two advantages. First, the well known cleaning and other technological procedures developed for silicon can be used. Second, the substrate can be chemically removed in order to get self supporting GaN templates for further growth. Therefore GaN grown on Si is of great interest despite the large misfit. Most research work has been done on the growth of GaN on Si substrates by MBE and MOCVD. LED's have been successfully fabricated on the subsequent structural materials. Due to the large differences in the thermal expansion coefficient and lattice constants between GaN and Si substrates, the cracks on the surface of GaN epilayers usually can hardly be avoided. As we know, the buffer layer is important for the quality of GaN on either Si epilayers or Si substrates. To improve the material quality even without any cracks, research workers have employed many kinds of buffer on Si substrates, such as SiC, A1O and GaAs etc. In this study, AlN self-assembled quantum dots (QDs) with a high density of \( \sim 4.4 \times 10^{10} / \text{cm}^2 \) on 0.2nm Si(111) substrates have been grown by low-pressure chemical vapor deposition using a MOCVD D1.35 system under a very low V/III ratio of 0.5%. We found that high quality QD/A1N buffer high quality GaN epilayers without cracks were grown even when the epilayer thickness reached to 3 microns. The successful growth of the large area crack-free GaN on Si substrates can be attributed to the strain relaxation by the underlying AlN. The quality and morphology of the GaN layers were investigated by X-ray rocking curves, transmission electron microscopy, transmission electron microscopy, high resolution X-ray diffraction and optical microscope.

Y10.37

Lateral Overgrowth of in situ SIN Masks for Low Dislocation Density GaN on Sapphire. Till Reiman1, Juergen Christen1, Zolt Miksa2, Bob Pezz1, Eric Frayssinet3, Bernard Benoist3, Jean-Pierre Pradier4 and Pierre Gilot5; 1Institut für Experimentelle Physik, Otto-von-Guericke-University, Magdeburg, Germany; 2Research Institute for Technical Physics and Materials Science, Hungarian Academy of Sciences, Budapest, Hungary; 3Université, Valilope, France.

For GaN growth on foreign substrates, a strong reduction of dislocation density is possible by masking techniques, e.g. Epitaxial Lateral Overgrowth (ELO) or Penetration Epitaxy. However, these techniques suffer from existence lithography steps. Additionally, highly defective masks (SiO) are typical for these methods. Device technology is difficult. An alternative approach [1] involves using an SIN slit-mask, which completely eliminates these problems and, if properly optimized, leads to similar results as for standard ELO material. We present Ultra Low Dislocation Density (ULD) GaN layers obtained by Metal Organic Vapor Phase Epitaxy (MOVPE). These layers with mask size were grown prior to the growth of the low temperature GaN buffer on sapphire substrate, leading to amorphous SiN islands of 20-40 nm lateral extension and 25nm height. This process induces a 3D nucleation at the early stages of GaN growth and is compatible with an ELO process on a random mask pattern. Cross-sectional spectrally resolved Cathodoluminescence Microscopy (CL) clearly visualizes a self-organized growth mechanism similar to two-step ELO on stripe masks. The initial part of the MOVPE sample, which corresponds to lateral growth and coalescence of the randomly distributed GaN islands, exhibits a weak peak due to the acceptor-free exciton and dominant (D\(^{+}\)X) emission (FWHM \( \sim 2.5 \) meV), which is also characteristic for the laterally grown regions of standard MOVPE-ELO. As in ELO, a strong lateral bending of threading dislocations (TDs) is visible in CL and directly evidenced by Transmission Electron Microscopy (TEM). Following the transition from lateral to overall (0001) growth, the upper part of the GaN layer exhibits sharp (D\(^{+}\)X) luminescence (FWHM \( \sim 2.5 \) meV) and a significant contribution of the free exciton to its excellent optical quality. At the sample surface, the TD density is well below \( 10^8 \text{cm}^{-2} \) for 10nm thick layers as independently measured by Atomic Force Microscopy, CL and TEM [1]. [S. Hafiez, H. Lakrche, P. Vennegs, B. Benoist, F. Ooms, and P. Gilot, Appl. Phys. Lett. 75, 1278 (1998)].

Y10.38


AlGaN/GaN field effect transistors (FETs) had recently been attracting much attention because of their promising uses for high-voltage, high-power, high-temperature microelectronic applications. We report the growth and characterization of AlGaN/GaN heterostructures grown simultaneously on three types of sapphire substrates in a multifour rotating disc low pressure MOCVD system (EMCVD D-125). Three substrates were used, one of which was an exact c-plane substrate, the other two were misoriented. The two other substrates, with and without step treatment, X-ray diffraction (XRD) measurement indicated that the Al composition of all three samples was 15%. X-ray rocking curves (XRC) for both symmetrical and asymmetrical reflections were applied to evaluate the crystal quality of AlGaN/GaN heterostructures. The FWHM of symmetrical (002) reflection did not show significant difference. But the asymmetrical (002) reflections decreased from 604 arcsec for c-plane substrate to 557 arcsec for misoriented 0.15°, and to 530 arcsec for step-treated. Scanning electron microscopy (SEM) was used to observe small pits, which seemed to be corresponding to the threading dislocations of AlGaN/GaN heterostructures. Cells of the density of the pits on c-plane substrate, on misoriented 0.15° and on step-treated were 1.2 \( \times 10^9 \), 1.1 \( \times 10^9 \) and 8.3 \( \times 10^8 \text{cm}^{-2} \), respectively. Finally, room temperature Hall-effect measurement was performed to measure the electron mobility. The electron mobility on c-plane substrate was 1200 \( \mu \text{m}^2/\text{V\cdot s} \) and that on misoriented 0.15° substrate was increased to 1400 \( \mu \text{m}^2/\text{V\cdot s} \). The electron mobility on step substrate was further improved to as high as 1500 \( \mu \text{m}^2/\text{V\cdot s} \). Sheet carrier density of c-plane sample was 8.0 \( \times 10^{13} \text{cm}^{-2} \). As a summary, it was found that misorientation and step treatment decrease the density of threading dislocations improving crystallinity of AlGaN/GaN heterostructures, resulting in the higher electron mobility.

Y10.39


A novel buffer layer structure has been investigated in order to improve the performance and to reduce the defect densities at the channel of an AlGaN/GaN heterostructure field effect transistor (HFET). This method employed multi-AlN buffer layers and incorporated AlGaN/GaN superlattices which transitively heated low-pressure MOCVD system has been used to grow highly uniform AlGaN/GaN heterostructures on (0001) sapphire or 4H-SiC (0001) 15°-deg-inch substrates. Growing incidence x-ray reflection (CIXRR) was used to evaluate the planarity of the channel heterointerface. These results were compared with atomic force microscopy (AFM) results and etch pit density studies of the material and confirm a significant improvement in the mean square roughness (RMS) surface roughness of these devices. Devices on both sapphire and silicon carbide have been grown and processed. Hall measurements of samples grown on sapphire substrates yielded mobilities as high as 2100 \( \mu \text{m}^2/\text{V\cdot s} \), and the sheet carrier density of (1) 1.3 \( \times 10^{13} \text{cm}^{-2} \) and 2250 cm\(^2\)/V and (2) 1.2 \( \times 10^{13} \text{cm}^{-2} \) on silicon carbide substrates accordingly. A significant dependence in the mobilities and carrier density on the growth temperature has been revealed. The trend likely reflects changes in the planarity of the heterointerface directly related to the
growth temperature. The DC characteristics of the devices showed transconductances above 200 mS/mm for a gate length greater than 2 microns. Results on shorter gate-length devices also will be presented.


Growth of metallic and reflecting ZnSe films is conducted on Si(111) at 500°C using a single-source molecular precursor Zn(SeH)$_2$ in a molecular-beam epitaxy chamber. Epitaxial growth of ZnSe(001) is accomplished despite the very large lattice mismatch between ZnSe and Si(111). High-resolution cross-sectional transmission electron microscopy and scanning electron microscopy images on Si(111) interface show a heteroepitaxial relationship involving a "magic mismatch" of coincidence lattices. The GaN films grown on the ZnSe/Si(111) template is virtually homoepitaxial because of the very small lattice mismatch, 0.06%, between the In-plane lattice parameters of ZnSe(001) and GaN(0001). The reflective nature of ZnSe surface presents an added advantage to optoelectronic applications of these nitrides grown on Si.


Group III-nitride alloys with mixing on the nitrogen sublattice, such as GaNAs, recently have attracted considerable attention. Theoretical predictions of direct band gap over the entire composition range, combined with anticipated high-band offsets, make these materials desirable for a number of potential optoelectronics applications. Successful incorporation of nitrogen in GaAs matrix and isoelectronic doping of GaN with arsenic have been demonstrated and studied by several groups. On the other hand, higher levels of arsenic incorporation in nitrogen-rich GaNAs are less thoroughly investigated due to a significant miscibility gap in the GaNAs system. In the present work, homogeneous GaNAs alloy films containing 3 to 4% of arsenic on an ion beam were grown on GaN templates by MOCVD at 700°C. Composition and structure of the films were characterized by electron probe microanalysis (EPMA), transmission electron microscopy (TEM), and x-ray diffraction (XRD). Some of the ternary GaNAs films were subjected to a post-growth annealing at 100°C in nitrogen ambient and compared to as-grown material. Due to the reaction of the GaNAs films to the nitrogen ambient, a new XRD pattern and an increase in the peak intensity of the GaNAs peaks in the transmission electron diffraction patterns. On the other hand, as-grown GaNAs films exhibited no evidence of binary phase segregation. Bandgap reduction due to alloying was observed by the optical transmission measurements, leading to an estimate for the bowing parameter of 25 eV in the films with the arsenic content of 3.5% - in keeping with the theoretical prediction of Bellmiche et al. (Phys. Rev. B 54, p. 17568 (1996)) of a significant degree of bandgap bowing in nitrogen-rich GaNAs alloys.

Y10.42 A study of the elemental interdiffusion in GaN/Si wafer grown by metalorganic vapor phase epitaxy. Xinxi A. Chen, Masaichis Ishikawa, Youkichi Kuroki, and Nobuhiro Shizuki. 1Toyota Central R&D Labs. Inc., Nagakute-cho, Japan; 2Nagoya University, Nagoya.

In order to fabricate high qualified photon and electric devices based on GaN/Si material with vertical structure, a good understanding of the heterointerfaces, especially the epitaxial film/Si interface, in the wafer is necessary. Secondary ion mass spectrometry (SIMS) investigation on GaN/Si samples grown by metalorganic vapor phase epitaxy (MOVPE) reveals a temperature dependence of interdiffusion at the epitaxial film/Si interface. Increasing growth temperature will increase the penetration depth of high Al concentration region in the substrate, which might result in an inadvertent junction in the n-Si. Photocurrent spectroscopy measurement on the sample shows, when a light with energy lower than the GaN bandgap is incident on the sample from the GaN side, a

current flowing from the Si side to the GaN side occurs under zero bias voltage. It indicates that the hetero-epitaxy growth brings an internal electric field into the GaN/Si structure.


AlN and GaN films with AlN buffer layers were deposited on Si(111) substrates via metalorganic vapor phase epitaxy using varying times of Al pre-flows prior to AlN growth. Atomic force microscopy (AFM) was used to determine the influence of Al pre-flow times on the surface morphology of the AlN and GaN films. When preceded by a 10 second Al pre-flow, AlN films feature an increased and more uniform nucleation density as compared to films deposited without Al pre-flows. Ten second Al pre-flows were also found to result in a reduction of the RMS roughness for 100 nm thick AlN films from 2.7 nm to 0.9 nm. AFM of 0.5 µm thick GaN films deposited on AlN buffers with varying pre-flow times showed reduced roughness and increased pit density when compared to AlN pre-flow for 2 seconds. High resolution x-ray diffraction of the GaN films showed a reduction in the average full-width half-maximum (FWHM) of the GaN (002) reflection from 1100 arcsec to 870 arcsec when the AlN buffer layer was preceded with a 10 second Al pre-flow. Increasing the pre-flow time to 20 seconds and 30 seconds resulted in average (002) FWHM values of 898 arcsec and 1570 arcsec respectively. Similar behavior of the peak widths was observed for the (303) and (103) reflections when the pre-flow times were varied from 0 to 30 seconds.

Y10.44 Effects of Cu-ion implantation into epitaxial (Ga,Al)N films grown by metalorganic vapor deposition. Z. J. Beekman, M. D. McNeil, D. B. Heath, D. J. Nichol, J. Ferguson, J. A. Senante, and N. Dietz. 1Electrical & Computer Engineering, Georgia Institute of Technology, Atlanta, Georgia; 2Physics, Georgia State University, Atlanta, Georgia.

Ion implantation into a variety of epitaxial GaN, AlN and AIGaN films grown on sapphire by Metalorganic Chemical Vapor Deposition (MOCVD) has been performed. Secondary ion mass spectrometry (SIMS) data similar to the theoretical simulation, showed the Cu-implants to have maximum concentration values of about 1.018 per cubic centimeter near 0.1 nm and continue to a depth beyond 5.5 nm with an implantation energy of 200 keV at both room temperature and 77 K. Cu implantation into (Ga,Al)N grown by metalorganic vapor deposition (BARCVD), Raman, and Fourier transform infrared (FTIR) spectroscopy were used to characterize the crystalline damage and structural variation of nitrides due to Cu-implantation and the recovery from the subsequent high-temperature annealing (780-900°C) annealing in an N$_2$ ambient (002) 2Theta-2-Omega pattern, Cu-implanted GaN exhibited an additional band at ~0.43 degree below the GaN (0004) peak, which disappeared after rapid thermal annealing (RTA) at 780°C. Raman and FTIR data indicated, however, that this damage was apparent due to the crystal structure recovery after RFA. UV-visible transmission measurements revealed two absorption bands in AIN due to Cu-implantation, located at ~1.5 and ~3.8 eV below the AlN band edge absorption at 6.2 eV. An absorption band from Cu-implanted GaN and AIGaN (1.5%) is found at ~0.89 eV and ~0.73 eV, respectively, below their corresponding band gaps. Low temperature photoluminescence (PL) for Cu-implanted and unimplanted GaN showed the effect of crystalline damage due to the Cu-implantation and recovery of GaN features. The donor-acceptor pair (DAP) features are observed below 3.35 eV and their intensities are varied with the annealing temperature. Discussion is given in comparison with Cu-implantation into GaAs performed in early years.

Y10.45 Real-Time Optical Monitoring of InN Gas Phase Kinetics at Elevated Pressures. N. Dietz, H. Bohn, P. Strannub and V. Winding. Physics & Astronomy, Georgia State University, Atlanta, Georgia.

Gaining insights in the growth kinetics of nitrides and consequences of heteroepitaxial thin films is crucial for controlling a chemical vapor deposition process, since it defines the perfection of the heteroepitaxial film both in terms of extended defect formation and chemical integrity of the interface. The here presented research focuses on the real-time optical monitoring of gas phase and surface chemistry processes during the heteroepitaxial nucleation and growth of InN layers on sapphire substrates. A high pressure metalorganic vapor deposition HP-CVD reactor with integrated optical diagnostics to
Silicon doping in InGaN/GaN quantum wells (QWs) has been widely used in fabricating high-performance light-emitting devices. Without silicon doping, the effects of growth mode change, microstructure, strain relaxation, and piezoelectric field screening have been reported. However, various previous studies of silicon doping have focused on the samples emitting purple-blue photons. Usually, it is difficult to achieve uniform InGaN alloy, particularly with high indium contents. This is so due to the solid phase immiscibility and phase separation, which stems from the large lattice constant mismatch between GaN and InN. In this paper, we report the characteristics of stimulated emission (SE) gain, of high indium [in the green range].

InGaN/GaN QWs. The results of relatively low-indium-content QWs were compared to show the effects of indium content variation. In our results, only the sample of high-indium and barrier doping shows the multi-peak SE feature that is quite different from previously reported. The SE spectra of the un-doped and well-doped samples of high-indium content show only a high-indium content samples, the SE peaks appear on the high-energy side of PL spectra that can be explained with the emission from the carriers confined in the localized states of indium-rich clusters. In our previous studies, it has been found that silicon doping in InGaN/GaN QWs could strongly affect the nanostructures. In particular, quantum-dot-like structures could be formed. Such a phenomenon was especially clear in barrier-doped samples. Therefore, we may interpret the multi-peak feature of SE in the high-indium barrier-doped sample as the contributions of quantized states in quantum dots of different sizes, compositions, or shapes. Hence, the observed peak merging behavior when temperature was raised explains the complicated interaction of thermal carriers among different energy levels and neighboring locations of different potential minima.

**Y10.46**

**Novel Method for the Activation of Acceptor Dopant in AlN Introducing Localized Band by In-electronic Donat**

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Controlled p-type doping into nitride semiconductors is crucial for the development of optoelectronic devices. In this study we propose a novel method to activate acceptor dopants in AlN by introducing in-electronic dopant, and have theoretically demonstrated using first-principles method. The acceptor dopant in AlN makes deep acceptor level (more than 100 meV) and generates few hole carriers into the valence band because of large affinity of N. On the other hand, incorporation with group-III in-electronic dopant (P, As and Sb) that has small affinity compared with Ni into AlN makes localized band upward the valence band maximum [VBM], and its energy offset from VBM is higher than that of the acceptor level. When both acceptor dopant and in-electronic dopant are incorporated into AlN, holes created by acceptor dopant can be easily activated by small affinity of in-electronic dopant, and can move in the localized band. We have verified this novel p-type material, Mg-doped p-AlN, using first-principles pseudopotential method. 256 supercells are employed in this study. As a calculational result, incorporation of P [less than 0.25 %] and As [less than 1.5 %] makes localized band upward VBM of AlN, and moreover the energy offset of localized band approximately corresponds to VBM of GaN [8.37 eV]. The incorporation of acceptor dopant Mg into AlN decreases the Fermi level from ~2.35 eV to ~0.33 eV, whereas the conventional Mg-doped AlN still has a deep acceptor level. Accordingly hole concentration drastically increases in the localized band and can be effectively injected into VBM of GaN. Consequently novel p-type material, p-AlN, is very effective to inject hole current into VBM of GaN.

The author acknowledges Prof. James S. Harris at Stanford University for use of first-principles programs.

**Y10.45**

**In situ real time characteristics of long-range and short-range surface morphology change during ion beam assisted epitaxy of GaN, Bence Cai** 1, 2 and Philip I Cohen 1, 2

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Periodic patterns have been induced by low-energy ion bombardment [1]. In the current work, in-situ, real-time light scattering combined with Reflection High Energy Electron Diffraction (RHEED), X-ray photoelectron spectroscopy (XPS), and Ion Beam Scattering (IBS) were used to study the evolution of the surface morphology of GaN during ion beam assisted MBE growth. Ga was provided by a thermal effusion cell; amonun was used as the nitrogen source. A hot filament Kaufman ion source was used to supply sub-keV ions beams. Sapphire and MOVCVD GaN templates were used as the substrates. A Description Mass Spectrometer (DMS) was used to calibrate the growth temperature. Before growing GaN, the sapphire substrates were treated in an iodine flame for 30 min. The sapphire surface was then nitrided in ammonia at 1100K for about 10
min. After nitridation, a thin GaN buffer layer was prepared by a sequence of submersion and annealing steps. During the growth, the short-range surface morphology and film thickness were monitored in situ by RHEED. In a real-time way, the long-range surface morphology was monitored in situ by light scattering technique. Plasmon detector and CCD camera were used to record the reflected light scattering intensity and spatial profile respectively. A gratings-patterned GANWs was used first to study the ion bombardment effects on periodic surface morphology. Preliminary results showed that the light scattering reflection beam intensity decrease when annealing at 1000°C for 30 min 500 eV Ar ions bombardment from a glancing angle, the 01 reflection beam intensity increased by 50%, while the specular beam intensity decreased by 50%. Roughness parameters such as surface width, surface correlation length, and the roughness exponent, can be extracted from the light scattering profiles and will be compared to that obtained from AFM. Partially supported by the National Science Foundation and the Air Force Office of Scientific Research. J. J. Ehrlicher, M. J. Aziz, E. Chason, M. B. Sinclair, J. A. Flora, Rev. Lett. 82, 2530 (1998). J. J. Ehrlicher, M. J. Aziz, E. Chason, M. B. Sinclair, and J. A. Flora, Phys. Rev. Lett. 84, 5800 (2000).

Y10.51


The use of H2O or other high-k dielectrics as a passivation layer on GaN-based high voltage devices and as a gate insulator in field effect transistor (FET) devices requires knowledge of the band alignment of this interface. Photoemission spectroscopy has been used to observe the band edges in the H2O layer deposited on n-type GaN(0001). The H2O layer is formed by reduced deposition of several monolayers of H2O by direct beam deposition from a Knudsen cell. The H2O layer is then annealed to 550 °C to form the interface. The as-grown GaN/H2O interface showed an increase in upward band bending from the clean surface of 0.5 eV giving a type II valence band offset (VBO) of ~0.1 eV. The 550 °C anneal resulted in a ~0.5 eV change in band bending and band offset. The final annealed interface exhibited a type II VBO of 0.3 eV and a conduction band offset of 2.1 eV. The variation of the band offsets after annealing appears to be related to excess oxygen in the H2O layer. These results deviate from the electron affinity band offset model by ~0.2 eV. Research supported by the ONR.

Y10.52

Radiative and non-radiative emission channels competition in thick HVPE-GaN layers grown on PENDEO templates. Eugenio Yacinesh*1, Tsuyoshi Poskunov*2, Pieter Poskunov*2, Bo Monene*2, Anna Koskovskii*2 and Robert Düns*2. 1Institute of Physics and Measurement Technology, Linköping University, Linköping, Sweden; 2North Carolina State University, Raleigh, North Dakota.

The difficulties of bulk GaN growth and the lack of lattice matched substrates for heteroepitaxy is the reason for dislocation densities of 10^8–10^9 cm^-2 in the GaN epilayers, which limits the performance of the devices produced on such material. There has been great interest in developing buffers that, though involving more complex processes, can decrease the dislocation density further, to the range of 10^6–10^7 cm^-2. The technology for growth of complex buffers involves patterning or special processing prior to growth. A term of interest is the investigation of emission properties in relation to the impurity redistribution in the overgrown material. An approach to perform mask-free selective lateral epitaxial growth is the PENDEO-epitaxy. In this work, thick GaN layers are grown by hydride vapour phase epitaxy (HVPE) on templates performed by mask-free selective PENDEO-epitaxy. The defect distribution relative to the different growth modes is investigated by transmission electron microscopy. The spatially resolved emission profile at different wavelengths is examined by cathodoluminescence and correlated to the different character of the growth and the distribution of the defects and impurities. Areas of enhanced as well as reduced emission are observed and are related to enhanced radiative or non-radiative competing mechanisms. A change of the dislocation densities, their directions of propagation and type are observed. The change in the intensities of the donor bound excition emission, donor-acceptor pair emission and free electron recombination band in the spectra taken at different areas suggests a redistribution of donor-acceptor pairs or impurities with respect to the point defects, which in turn is related to the dominating growth mode in different areas.

Y10.53

The RIE Fabrication and the Ultra-high Temperature (150°C) Anneling of the GaN Nano-rods, Huijiang Yu1,2, Lee McCarty3, Stacia Keller3, Steven DenBaars4,5, James Speck3,1, and Umesh Mishra1. 1Materials Department, UCSB, Santa Barbara, California; 2ERATO JST, UCB, Santa Barbara, California; 3Department of Electrical and Computer Engineering, UCSB, Santa Barbara, California.


Y10.54

Non-uniform distribution of interband transition wavelength in MOVPE-grown AlN/GaN multiple quantum wells over a 2-inch substrate. Ichitaro Waki, Chiyuki Kumomkritikul1,2, Yukihiko Shimomura1,2 and Yoshiaki Nakano1,2. 1JST-CREST, Tokyo, Japan; 2CAST-Univ. of Tokyo, Tokyo, Japan; 3Dep. of Materials Eng-Univ. of Tokyo, Tokyo, Japan.

Interband transitions (IBTs) in quantum well (QW) structures are unique and can be applied to future optical devices, such as ultrathin all-optical switches, detectors, and modulators in monolithic cascade lasers. Among many material systems, nitrides are very attractive because of their intrinsic material properties. However, the growth of such nitride-based QW structures for IBT is difficult, particularly by metalorganic vapor phase epitaxy (MOVPE), due to the necessity for fabricating atomic DC heterointerfaces in the QW. Recently, we realized a new phase of IBT at a wavelength of 1.98 µm by MOVPE for the first time. To achieve the atomic DC heterointerfaces of the AlN/GaN multiple QW by MOVPE, we used GaN multilayer layers. Consequently, the heterointerfaces of the samples were found to be comparable to or better than the molecular-beam epitaxy grown samples. Though a short-wavelength IBT was observed, a small full-width at half-maximum of the 532 nm peak was achieved by MOVPE, the role of the multilayer layers is still not fully understood. We therefore believe that a detailed study on a correlation between the IBT and the structural quality is necessary for further improvement of the MOVPE grown QW samples. In this study, a high-quality 150-period AlN/1.05 nm GaN/Si (1.65 nm) multiple QW was grown on a (0001) sapphire substrate using the same technology. An IBT at a wavelength of 1.72 µm was observed by optical absorption measurements at the center of the 532 nm peak. We also observed a blue-shifting of the IBT wavelength from 1.72 to 1.52 µm in the measurement procedure was changed from the center to the edge of the wafer, though the structural difference between the IBT and the peak was negligible. This phenomenon was investigated in terms of an inhomogeneous distribution of a built-in electric field in the QW.
ferromagnetism with over 2% of the Cr magnetically active at room temperature. Electrical measurements indicate that these films follow the conventional Kerr law, but significant deviations from it have been observed over a range between localized states in the impurity band is the dominant transport mechanism. A more complete description of the electrical, magnetic, and optical properties will be reviewed.

Y10.58 Carbon doping of Gallium Nitride using Carbon Tetra
bromide in rf plasma MBE. Daniel S Green1, Sridharraj Rajani1,
Unmesh K Mishra1 and James S Speck2, 1Electrical and Computer
Engineering Department, University of California, Santa Barbara, California, 2Materials Department, University of California, Santa Barbara, California.

Carbon is one of the three most common impurities in GaN along with hydrogen and oxygen. Yet while oxygen is understood to be a shallow donor and hydrogen is found to occupy a deep donor level, the behavior of carbon is still poorly understood. Carbon is thought to be useful either as a shallow acceptor to produce p-type GaN or as a deep level to produce semi-insulating GaN. The carbon site is predicted to depend on the surface condition and the Fermi level during growth with the carbon generally anticipated to occupy substitutional or interstitial sites which compensate other intentional dopants and self-compensate in the case of carbon in the primary dopant. To investigate the role of carbon in GaN, Carbon Tetra
bromide (CBr4) was used to dope GaN grown by rf plasma MBE. CBr4 is regularly used to introduce carbon as a shallow acceptor in other III-V semiconductors and therefore is a mature technology available for MBE systems. Films were grown homoepitaxially on semi-insulating MOCVD grown substrates under Mg- and N-rich conditions. The growth rate was ~200 nm/hr for an rf plasma power of 150W. The CBr4 flux was studied over a range ~1510 to 2110 Torr and the substrate temperature was varied from 600°C to 650°C. Additional films were grown with GaN and co-doped with hydrogen, silicon and carbon. The samples were characterized by SIMS, AFM, Hall, and CV profiling. SIMS measurements revealed that the carbon readily incorporates under Ga-rich as well as N-rich growth conditions and yield increased concentrations of ~2x1017 to ~2x1019 cm-3 for the range of C source flux. Further, the Ga-rich growth conditions yielded sharp doping profiles (~8 nm/dec). The carbon incorporation is compatible for Ga-rich and N-rich growth, but decreased for increased substrate temperature. AFM measurements showed the surface morphology is typical of undoped GaN indicating no adverse impact of the carbon doping, in contrast to etching reported when CC4 is used as the dopant source. Hall measurements of the silicon and carbon co-doped samples with silicon doping of ~1x1018 were shown to have the carrier concentration reduced as the carbon concentration increased, and were resistive when the carbon doping exceeded the silicon doping. However, further analysis of the compensation activity of the carbon was compromised by parallel conduction found at the regrowth interface. CV profiling verified the insulating nature of GaN-C with carrier densities less than 1x1016 cm-3, and the presence of a charge of ~1x1018 cm-3 at the regrowth interface.

Y10.59 Activation Of Beryllium Doped GaN Grown By RF-Plasma
Molecular Beam Epitaxy. Yuandong Liu, Kyoyoung Lee, Craig
Swartz, Thomas H Myron, Jun Wang and Norman C. MacDonald. West
Virginia University, Morgantown, West Virginia.

Beryllium doping has been investigated for GaN grown by rf-plasma molecular beam epitaxy on Ga-polar MOCVD grown GaN templates. All samples were grown with a growth rate of ~0.37 µm/hr. A step-doped sample with 0.5 µm Be-doped steps with 0.5 µm undoped spacers was analyzed by Secondary Ion Mass Spectrometry (SIMS). This sample exhibited symmetric steps for dopant incorporation of 1017, 1018 and 1019 cm-3. A series of 1 µm thick uniformly Be-doped films were grown on 0.1 µm of undoped GaN. Resistivity measurements with pressed indium contacts indicate that all uniform Be-doped samples were semi-insulating. Samples were annealed after growth at atmospheric pressure in a tube furnace utilizing a two-stage process. The first anneal stage was in flowing forming gas (3% H2 in N2) for up to 3 hours at temperatures ranging from 600°C to 800°C. The second stage was in flowing nitrogen at 800°C for 1 to 3 hours. All samples were inspected before and after the anneal with an Olympus BX51M microscope with a UV fluorescence attachment. As-grown samples were colorless in air. As-grown samples doped heavily with Be (above ~1x1018 cm-3) exhibit orange UV fluorescence, and is likely associated with inversion domain formation, bringing the N-polar face to the growth surface. As-grown samples that exhibit this orange fluorescence have been found to be semi-insulating through etching experiments. The annealing process activated the orange UV fluorescence for the samples doped at about 1x1018 cm-3, while those with less dopant levels remained blue. All samples remained semi-insulating after the anneal. This work was supported at WVU by ONR under grants N00014-02-1-0974 and
Y10.60 Mg doping of GaN with RF-Plasma molecular beam epitaxy.
Czeslaw Skierbiszewski, 1 Marcin Siekacz, 1 Anna Feduniwicz, 1 Zbyszek Wnukiewicz, 1 Seymon Grunzak, 1 Boguslaw Pustaczuk, 1 Michal Leszczynski, 1 Slawojez Pawlowski 1
1High Pressure Research Center, Wunsdorf, Poland; 2Institute for Microstructural Sciences, National Research Council, Ottawa, Ontario, Canada.

GaN:Mg layers were grown by molecular beam epitaxy (MBE) using RF-Plasma source as a nitrogen precursor. Contrary to the GaN:Mg layers grown with ammonia, our samples do not contain hydrogen and p-type conductivity can be achieved without any post growth treatment. The MBE system very attractive for research of p-type doping of GaN. We investigated growth of the Mg doped GaN layers on sapphire/MOCVD templates and on GaN bulk crystals. Secondary Ion Mass Spectrometry (SIMS) showed that the Mg incorporation into our layers changes linearly with the Mg flux measured by Monitor Ion Gage. Drastic improvement of the Mg doping was obtained at lower growth temperatures. For given Mg flux we were able to increase the Mg concentration measured by SIMS by 2 orders of magnitude from 1.1 to 3.5 cm⁻²/√s.

Y10.61 MBE Grown AlN Films on SiC for Piezoelectric MEMS Sensors. Dharampal Doppalapudi 1, Richard Michal 2, Jeffrey Cheung 1, Harry Fuller 1, Anirban Bluthecharony 1 and Theodore Moussoukis, 1 Boston Micro Systems, 2Wakum Information, 1Electrical and Computer Engineering, Boston University, Boston, Massachusetts.

Microelectromechanical Systems (MEMS) are being extensively investigated for minimizing various piezoelectric sensors. Due to the advantages of smaller size, lower power consumption, higher sensitivity and the ability to form compact multi-sensor arrays, such devices typically employ one or more silicon micromechanical elements (membranes, cantilever beams, tethered ground masses, etc.) and a polycrystalline piezoelectric film. The use of polycrystalline materials results in inherently less stable and irreproducible device characteristics due to difficulties in replacing the polycrystalline film with a single-crystal material. In contrast, epitaxial films grown on single crystal micromechanical elements result in highly reproducible and stable devices with improved performance. AlN, in particular, has excellent piezoelectric properties for microsensor applications. In this work, we use an electric coupling coefficient of 0.088 and a high in-plane acoustic velocity (~5700 m/s). In this paper, we present a single crystal SiC-AlN piezoelectric MEMS sensor platform fabricated by integrating MBE-grown AlN films onto photoelectrochemically machined SiC microelectromechanical structures (microcantilevers, membranes etc). SiC and AlN have excellent lattice and thermal match enabling growth of high quality epitaxial piezoelectric films with negligible internal stress. AIN and SiC also have good acoustic match and chemical stability, providing low-loss resonators capable of long-term operation in harsh sensor environments. Fabrication of piezoelectric AlN-SiC microresonators and flexural plate wave devices, and their application to chemical, biological, and fluid sensing, is reported. Integration of III-nitride materials with MEMS creates exciting new opportunities in optical devices, sensors, actuators and RF MEMS.

Y10.62 Effect of Buffer Design on AlGaN/AlN/GaN Heterostructures by MBE. Goh Namkong, 1 W. A. Doettingle, 1 A. S. Brown, 1 M. Laszlo, 1 M. Giampiero, 1 and G. Bruno, 1 1Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, Georgia; 2Electrical and Computer Engineering, Duke University, Durham, North Carolina; 3Institute of Ionizing Methodologies and of Plasma, IMIP-CNIR and INSTM, Bari, 47012 Italy.

A key issue for III-Nitride materials growth is the lack of high quality lattice-matched substrates. Recently, a comprehensive study of the effect of the initial growth conditions and layer design (i.e. nitridation and types of buffer layer) on the subsequent GaN epitaxial layers was reported [1]. In this work, we present the experimental results for this examined high temperature (700-850°C) AlN and combined AlN/GaN buffer layer effectiveness to produce Ga-polar GaN epitaxial layers grown by radio-frequency (rf) plasma Molecular Beam Epitaxy (MBE).

However, it is difficult to grow high quality AlN buffer layers due to the relatively low desorption rate and surface diffusion of Al, leading to the formation of misoriented (3D) growth and Al droplets. First, Al flux was increased from N-rich condition to Al-rich condition, which prevented the growth of AlN layer to avoid Al droplets. Second, under Al-rich condition, the Al shutter was toggled for 10 seconds for the first 2 minutes of growth. The etch pit density in GaN films was determined with hot phosphoric acid at 150°C for 30 minutes and the etch pit density was reduced from 100 cm⁻² to 10 cm⁻² in AlGaN/GaN heterostructures.


Gallium nitride (GaN) and Zinc oxide (ZnO) have the same wurtzite structure and nearly the same lattice constants. Therefore, ZnO single crystals are one of the candidates for the substrate of GaN films. In this study, GaN and its related films were grown on ZnO single crystals with 0001 (Zn face), 0001 (O face), 10-10 and 11-20 orientation using molecular beam epitaxy (MBE) method. The epitaxial relation of GaN films and ZnO substrates, the crystallinity of GaN films and the properties of the GaN films were characterized by X-ray diffractometry and X-ray rocking curve measured on X-ray diffractometers. The results of XRD and X-ray pole figure measurements indicate that the GaN films are grown epitaxially on the ZnO 0001 substrates. In these films, strong band-edge emission in the UV region was observed, and the intensity of emission was very low. The GaN films grown on ZnO with 10-10 and 11-20 orientation, the epitaxial relationship between GaN and ZnO was not simple, and the intensity of emission was very low. The structure and optical properties of the (In,Ga)N films grown on ZnO single crystals will be also discussed.

Y10.64 GaN Layers regrown on etched GaN templates by plasma assisted molecular beam epitaxy. Lei Li 1, Michael A. Reckshick, 1 Josh Proschild, 1 Jingyu Xue, 2 Fumiko Xue, 1, Xing Gu, 2 Feng Yun, 1 Allison A. Baski 1, and Hadin Morkoc 1, 2, 3, 4
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The growth of high quality GaN by plasma assisted molecular beam epitaxy (PA-MBE) is challenging, since GaN/AlN/GaN heteroepitaxy since GaN substrates are not yet commercially available and isotropic nature of growth. Due to the large lattice and thermal mismatch, the GaN films are grown on Sapphire substrate which in the grossly defective regions have been removed. In this work, we report the growth of GaN by PA-MBE on a Sapphire substrate in which the grossly defective regions have been removed. The GaN template is formed by MBE growth of GaN followed by wet chemical etching. The GaN film was then grown on the Sapphire substrate in which the grossly defective regions have been removed. Improved quality GaN was re-grown on such a template substrate. The growth of GaN on Sapphire substrate is successfully done, and the etch pit density of re-grown GaN is significantly lower than the GaN grown on Sapphire substrate. The etch pit density of re-grown GaN is lower than the GaN grown on Sapphire substrate.
re-growth initiating in regions free of extended defects. The results show that the selectively etched GaN on sapphire can be used as a good template to obtain high quality GaN.

Y10.05

Surface Control of ZnB$_2$ (001) Substrate for Molecular-Beam Epitaxy of GaN. Jun Suda, Hiroyuki Masumoto, Taenoku Kimoto and Hiroaki Matumoto, Department of Electronic Science & Engineering, Kyoto University, Kyoto, Japan.

Zirconium diboride (ZrB$_2$) has been proposed as a novel lattice-matched electrically-conductive substrate for GaN-based semiconductor [1-3]. We have demonstrated the first epitaxial growth of GaN on ZnB$_2$ (001) by molecular-beam epitaxy (MBE) [2]. However, the crystalline quality of grown layer was not enough for device applications. One of reasons is thought as cleanness of ZrB$_2$ surface before the growth. Since this compound has a very high melting point (3220°C), high temperature (1800°C) thermal flushing is required to prepare the substrate surface which is difficult to achieve such a high temperature in a standard MBE system. In fact, reflection high-energy electron diffraction (RHEED) from the ZrB$_2$ surface after thermal cleaning at 1800°C was found to be compared to that from the GaN grown layer, indicating insufficient cleaning. In this study, we have studied ZrB$_2$ surfaces by X-ray photoemission spectroscopy (XPS). Besides Zr and B, O was observed. The Zr peak splits into two peaks due to a chemical shift in the treatment, the intensity of O was much reduced and the peaks of Zr (bound to B) and B became dominant. The combination of suitable pretreatment and thermal cleaning resulted in sharp and intense RHEED from the ZrB$_2$ surface, leading process for the MBE growth of high-quality GaN/ZrB$_2$ substrates. [1] H. Kinoshita, S. Otani, S. Koyanagi, H. Amano, I. Akasaka, J. Suda and H. Masumoto, Jpn. J. Appl. Phys. 40 (2001) 272-239 [2] J. Suda and H. Masumoto, J. Crystal Growth 257-258 (2004) 111-114 [3] H. Kinoshita, S. Otani, S. Koyanagi, H. Amano, I. Akasaka, J. Suda and H. Masumoto, Jpn. J. Appl. Phys. 42 (2003) 2260-2263 [4] T. Akazawa, W. Hayami and S. Otani, Phys. Rev. B 65 (2002) 243403.

Y10.06

The Influence of Substrate Polarity on the Blue Emission from As-doped GaN Layers Grown by Molecular Beam Epitaxy. James Crowfoot, John F. Done, S. H. Pettigrew, S. R. G. T. Thompson, and J. R. C. Harrison. School of Physics and Astronomy, University of Nottingham, Nottingham, United Kingdom; 2School of Electrical and Electronic Engineering, University of Nottingham, Nottingham, United Kingdom; 3Chemical Engineering Department, University of Florida, Gainesville, Florida.

The observation of blue luminescence in GaN layers doped with arsenic initiated active research on growth of GaN layers doped with various group V isoelectronic dopants. Blue emission has been reported for As-doped GaN layers in both metalorganic vapour phase epitaxy (MOVPE) and plasma assisted molecular beam epitaxy (PA-MBE). Arsenic by GaN films grown by PA-MBE on GaN substrates show very strong blue emission at room temperature, which is more than one order of magnitude stronger than the MBE grown films. Our studies show that the observation of As incorporated into the GaN lattice during PA-MBE is strongly influenced by the choice of substrate and its polarity. To obtain blue deep level emission from As-doped GaN requires growth under Ga-rich conditions for both GaN substrates and (0001) GaN MOVPE templates. The exact conditions depend critically on the polarity of the GaN. To obtain strong blue emission a significantly higher GaN ratio is required when As-doped GaN is grown on Ga-polarity GaN (0001) template compared to N-polarity As-doped GaN on sapphire. The influence of the polarity of the substrate on the blue emission from As-doped GaN layers grown by PA-MBE was investigated further by extending the study to non-polar directions. Arsenic doped GaN layers were grown under identical PA-MBE conditions on several types of substrates including c-plane (0001) GaN, polar and non-polar GaN templates grown by MOVPE. Non-polar (1-1-20) and (1-1-10) GaN MOVPE templates were grown on a-plane (1-1-20) GaN and LIAO (11-20) substrates respectively. A strong influence of the substrate polarity on the optical properties of PA-MBE grown As-doped GaN layers was observed.

Y10.07

GaN Epitaxial Growth Process at High Growth Temperature by NH$_3$ Source Molecular Beam Epitaxy. Norik Oshino, Akiko Sugiura, Naoki Okabe and Naoyoshi Shiozawa; Advanced Materials Science & Eng., Yamaguchi University, Ube, Yamaguchi, Japan.

Annealing and epitaxial growth processes of GaN layer on sapphire (0001) at high growth temperatures above 9000°C using NH$_3$ source molecular beam epitaxy (MBE) have been investigated by observations of insitu reflection high energy electron diffraction and ex situ atomic force microscopy. It is found that the changing processes of the surface morphology and the island shape of the GaN buffer layer depended at a temperature of 900°C for 60 min strongly depend on the annealing temperature. It is noted that the surface morphology changed from islanding to columnar structure with flat surface by thermal annealing at 950°C. It is observed that the island shape of the GaN island is changed from a parabolic one to trapezoidal one with flat top surface. Furthermore, it is noted that the GaN continuous film with a flat surface is appeared at a growth temperature of 1000°C. It is considered that the growth kinetics of GaN epitaxial layer using NH$_3$ gas source MBE above 950°C is different from the GaN epitaxial layer at below 900°C. It is noted that the N-terminated surface is grown above 950°C and the surface contained hydrogen atoms desorbed during growth at a rate proportional to the growth temperature. Y10.08

Structural Characterization of Low-Temperature InN Buffer Layer Grown by RF-Molecular Beam Epitaxy. Tsumori Araki, Tomohiro Yamaguchi, MisaoKatouchi, Chiharu Morishita, Yasushi Nemoto and Akira Suzuki; 1Department of Photonics, Ritsumeikan University, Kusatsu, Japan; 2Research Organization of Science and Engineering, Ritsumeikan University, Kusatsu, Japan.

Recent developments of InN growth, especially in molecular beam epitaxy, have revealed the excellent electrical properties and new findings in the band-gap energy-gap relationship of InN. The bandwidths of InN-based nitride semiconductors such as high-speed electronic devices, long wavelength optical devices and solar cells. Usually InN films are grown on substrate like SiC, low temperature buffer layer. In this paper, low-temperature [LT] InN [1], LT-InN/LT-GaN [2] and high-temperature ALN [3] layers were used as the buffer layer and are found to be essential to obtain high quality InN films. However, InN films still has high density threading dislocations, large twist distribution and voids at interface between the film and the substrate. Therefore, the roles of the buffer layer in the InN growth should be understood for further improvements of the quality of InN films. In this paper, we will report on metalorganic microstructure of LT-InN buffer layer characterized by TEM. InN growth was performed by RF-MBE on (0001) sapphire. After nitridation of the substrates, a LT-InN buffer layer was grown at 300°C for 10 min (about 3nm) which followed by the InN growth at 520°C. The samples were observed with JEOL, 1010 and HITACHI H-9000HR electron microscopes operated at 200 kV and 300 kV, respectively. In the LT-InN buffer layer, defective regions were observed, which might be due to low temperature growth at 300°C. Three dimensional islands were also observed, in which growth orientation was disordered. These islands are found to be one of the origin of threading dislocations. [1] Y. Saito et al., Jpn. J. Appl. Phys. 40, L11 (2001); [2] M. Higashikawa et al., Jpn. J. Appl. Phys. 42, L540 (2003); [3] H. Li et al., Appl. Phys. Lett. 79, 1489 (2001).

Y10.09

Surface Termination Control of GaN Growth Using MOMBE. James Crowfoot, Philip C. E. Bunton, and John F. Done; 1Department of Chemical Engineering and Materials Science, University of Minnesota, Minneapolis, Minnesota, USA; 2Department of Electrical and Computer Engineering, University of Minnesota, Minneapolis, Minnesota, USA.

The growth and kinetics of GaN have been studied using metal organic molecular beam epitaxy (MOMBE) using triethylgallium (TEG) and ammonia (NH$_3$). Though different reconstructions are not observed, the adsorption of one and two layers of Ga is found to be observed in the decrease of the specular beam intensity when the ammonia flux is removed. A procedure is developed to allow growth under excess N conditions on one or two layers of Ga. The surprise is that under excess N conditions, smooth, step-flow growth is obtained even though substrate temperatures are near 750°C, typical of that used in Ga effusion cell MBE growth of GaN. Under MBE, similar conditions would correspond to diffusion limited, rough growth. Starting from MOVCD GaN templates, the growth and morphology under the different terminations was compared. Under excess N conditions, ammonia pressures were 5x10$^{-9}$ torr and the TEG pressure was 1x10$^{-5}$ torr. Based on the observed crossover and known ammonia dissociation, we estimate that at these conditions, the TEG dissociation rate is about 1%. Under excess N conditions on a native oxide substrate, hillock growth was observed with hillock lengths of about 40 nm. The ammonia flux was then decreased, keeping the TEG flux constant, changing to a termination of one layer of Ga. Under these conditions the hillock length remained above 100 nm, even though the growth rate was roughly the same. This suggests a change in the etch-step energy. On these surfaces no step bunching was observed, in contrast to previous
MOCVD work at similar growth temperatures.

Y10.70 Polarity inversion and in-plane periodic polarity structures based on GaN. Sebastien Perzyna, Nicolas Grandjean and Philippe Vennegues. CNRS-CTRREA, Valbonne, France.

It is observed during the growth by NHE3 molecular beam epitaxy of GaN that a polarity inversion from Ga to N occurs when a large Mg is used. The interface between the two polarities is perfectly flat over a 2 inch wafer, no dislocation is introduced by the growth process. Actually, the quality of the N-polarity GaN growing layer replicates that of the Ga-polarity underlayer. Transmission electron microscopy (TEM) images reveal a faceted interface. Secondary ion mass spectroscopy shows that the critical Mg concentration for a polarity inversion must be larger than 3x10^{11} cm^{-2}. Despite these indications about the role of the Mg, the actual mechanism responsible for the polarity inversion is still unclear. Furthermore, if the growth proceeds with the N-polarity underlayer and a large Mg is used, the GaN layer undergoes a crystal phase transition from hexagonal to cubic; the interface between Ga- and N-GaN being perfectly flat at the atomic scale. On a sample with a single GaN polarity inversion along the growth axis, stripes have been etched up to the Ga polarity by reactive ion etching. At this stage the sample exhibits an in-plane GaN-periodic polarity modulation. GaN is then overgrown in order to achieve thick periodic polarity structures. The vertical polarity domain boundary is investigated by TEM as a function of stripe orientations. Selective wet etching using KOH reveals smooth (110) planes for properly chosen stripe orientation.

Y10.71 Characterization of Photovoltaic Cells Using n-In/p-Si Grown by RF-MBE. Chahar Muirzad, Tomohiro Yamaguchi, Tsutomu Araki, Yasushi Nishiki, Akira Suzuki and Hiroaki Naoi. Dept. of Electrical Engineering, Ritsumeikan University, Shiga, Japan.

A newly established narrow band gap for indium nitride [InN] means that the indium gallium nitride system of alloys [InGaN:OxN] covers the almost full solar spectrum. Therefore, InGaN:OxN is a promising material for high-efficiency solar cells. In this paper, we characterized, for the first time, the photovoltaic properties of the InN:OxN structure formed by epitaxial n-InN/p-Si heterojunction grown by radio frequency molecular beam epitaxy [RF-MBE]. The n-InN/p-Si heterojunction was formed by epitaxial n-InN films grown on p-Si(111) and p-Si(100) substrates by RF-MBE. The substrates were of p-type conductivity with a resistivity of 0.03-10 Ω cm. Thickness of Si substrates was 370-530 nm. Growth rate of InN films was approximately 550 nm/h. The surface morphology of InN films was smooth and flat. The material employed for ohmic contacts was Aluminum, which was deposited by conventional vacuum evaporation. On the surface of InN films, circular electrodes with a diameter of 1 mm were formed; the back side of Si substrate was entirely covered by the electrode. The size of the sample was 0.5 cm x 0.5 cm. Dark L-V characteristics and L-V characterization in an air mass 1.5 global (AM 1.5G) condition using a solid-simulated illumination were measured at room temperature. The dark L-V characteristics showed clear rectifying characteristics. L-V characteristics in an AM 1.5G condition showed a photovoltaic effect. The short-circuit current was $I_{sc}=3.95$ mA/cm$^2$ and the open-circuit voltage was $V_{oc}=0.85$ V. Further studies should be necessary for the improvement of the photovoltaic properties, but these results clearly demonstrate for the first time the potential for realization of solar cells using InN-based materials.


So far, we have reported the room-temperature epitaxial growth of several oxide films by laser MBE, i.e. pulsed laser deposition in ultrahigh vacuum. Laser MBE technique supplying highly excited film precursors is very useful for the high-quality epitaxial growth of oxide films. On the other hand, we have examined the polarity of wurzite GaN films using in-situ atomic impact ion scattering spectroscopy (CAISS), in order to elucidate the atomic-scale growth behavior of nitride films. In this paper, we report on the low-temperature (close to room-temperature) epitaxial growth of ultrasmooth AlN films by laser MBE method using AlN target as well as the polarity characterization. AlN thin films were deposited on sapphire [0001] substrate without any buffer layers by laser MBE with RF excimer laser [wavelength; 148 nm, 20 mJ pulse, 5 Hz]. The films were characterized by RHEED, CAISS, XRD, AFM, and XPS. In the case of using a buffer layer of NiO(10 nm thick) we could grow the epitaxial AlN film at room-temperature. The RHEED pattern of re-deposited AlN film was streaky, and XRD analysis indicated that AlN films grew epitaxially with [0001] orientation. Surface morphology of the AlN epitaxial film grown at room-temperature showed the atomic step structure with smooth terraces. We also present the effects of buffer layers and substrate nitridation on the growth direction, 4° or 6° of AlN epitaxial films.

Y10.73 Growth of (Ga,Mn)N: A Diluted Magnetic Semiconductor by Chemical Beam Epitaxy (CBE). Angela Carrión, Chris Boney, Alexandre Litvinschik, Abdellah Benzenaïth, Chemistry, Technion. Tel-Aviv, Israel. *TeCSAM, Univ. of Houston, Houston, Texas, Texas Instruments, Univ. of Houston, Houston, Texas, &Raman Spectroscopy:TeCSAM, Univ. of Houston, Houston, Texas.

The GaN material system is a very promising candidate for the realization of electronic devices based on diluted magnetic semiconductors (DMS). The incentive behind studying DMS materials is their potential to form high-density magnetic memory integrated ICs, semiconductor based magnetic sensors, magnetic optical devices for communication systems, and other spin-based and photonic applications. Many reports have indicated that high doping levels of Mn in GaN lead to ferromagnetic materials with Curie temperatures at or above room temperature. To date, (Ga,Mn)N has been fabricated by several epipolar and non-epipolar techniques. However, to our knowledge, we are the first to report the epitaxial growth of (Ga,Mn)N by CBE. Deposition of (Ga,Mn)N on Si substrates using TEG, NH$_3$, and sold Mn as precursors. Bright 3D RHEED images exhibiting the six-fold streaky (1x1) patterns have been obtained, suggesting retention of the wurzite structure. Very small FWHM (Ga,Mn)N films grown on Si substrates. The FWHM ratio between 0.5-2.0% as determined by EMPA and XPS. XPS depth profiling verified the Mn is of uniform concentration throughout the films and XRD scans have not detected the presence of secondary phases besides the wurzite structure. In addition to RHEED, the CBE chamber employs two Time of Flight Ion Scattering Spectroscopy techniques, Direct Recoiled Scanning Spectroscopy (DRS) and Mass Spectroscopy of Recoiled Ions (MSRI). MSRI has been used as an in situ, real time technique, which allows the surface composition information of film components and impurities to be determined during the growth process. DRS has been used to: (1) monitor the efficiency of the degrading process in removing carbon impurities from the growth chamber. (2) prepare a continuous and uniformly doped Mn substrate. (3) determine the incorporation of Mn into the GaN matrix in order to correlate Mn incorporation rates with growth parameters. DRS is also capable of determining structural characteristics of the outermost atomic layers of the surface. Scattering-recoiling scans at a grazing angle determined that all samples are metal polycrystal., which was confirmed by characterization. The GaN material is partially polarized GaN, and the relative intensity as a function of the azimuthal rotation was consistent with published data by Amin et al. Data from (Ga,Mn)N surfaces are being analyzed to establish our study of the structure of the crystal. Raman spectra showed characteristic GaN signals in addition to two unreported previously peaks appearing in all (Ga,Mn)N samples at 605.3 and 763.8 cm$^{-1}$. Detailed analysis of these signals and their possible correlation with Mn concentration is being established. Magnetic properties characterization of the (Ga,Mn)N films is currently underway and will be reported.


A variety of different crucible materials have been suggested and/or employed for the sublimation-condensation growth of AlN single crystals above 2000°C. Representative materials all have melting points well above 2000°C, reasonable chemical compatibility with AlN, relatively low vapor pressures, and reasonable small thermal expansion coefficients. We analyze the current state of knowledge on crucible materials and how they impact growth of AlN single crystals. The materials include BN, AlN, HN, HC, Te, ThC, TaC, SnC, ZrC and ZrN with respect to published bulk AlN growth conditions. Crucible materials' pyrolytic graphite, pyrolytic BN, and W have integrated thermal contraction values (e.g. cooling from growth temperatures) that are less than that of AlN; the other materials have larger values. The lowest vapor pressure materials in a nitrogen atmosphere are W, TaC, and Re; thus they are expected or have been shown to yield higher purity crystals than the other crucibles. The materials C, BN, Hf, and ZrN yield
higher impurity levels in the AlN crystals.

Y10.75

Highly luminescent GaN powders have been synthesized by reacting high purity gallium metal with ultra-high purity ammonia. The resulting GaN powders are thousands of times more cathodo- and photo-luminescent than other GaN powders including commercially available material. Their luminescence intensities are comparable to that of GaN grown by hydride vapor phase epitaxy. GaN powders have many possible applications including electroluminescent lamps in appliances such as cell phones and car dash boards. GaN powders can also be used as precursors for growth of GaN thin films by pulsed laser deposition. Several improvements have been made on the synthesis technique developed by Johnson et al.[1]. One of the key reasons for the hexagonal GaN powders with high luminescence efficiency without the need for post-growth treatment. The material has been obtained by a complete reaction between high purity gallium metal (99.999%) and ultra-high purity ammonia (99.9999%) in a horizontal quartz tube reactor at 1000 °C. The powders produced in this reactor consist of light grey micro-crystals with wurtzite structure. Elemental analysis indicates that the powders obtained by this method have a high nitrogen concentration (more than stoichiometric GaN, 16.7%).

Powder X-ray diffraction demonstrates that the material has a high purity and single crystalline structure. Electron microscopy shows that the powder consists of at least two kinds of particles, small sized platelets and large sized needles. The GaN powders obtained by this method produce high efficiency ultra-violet luminescence around 370 nm (3.3 eV, near band-edge emission) when they are excited by accelerated electrons (cathodoluminescence) or by photons (photoluminescence) at room temperature. [1] W.C. Johnson, J.B. Parace, and M.C. Crew, J. Phys. Chem., 36, 2651 (1932).

Y10.76
Ultra-Thin Silicon Nitride Layers for GaN Epitaxy on Si(111). Thomas Schmidt, Torben Claussen, Sababhusan Gangopadhyay, Jens Falta, Luca Gregoratti, Mayn Kukinova and Stefan Hoefn. Department of Solid State Physics, University of Bremen, Bremen, Germany; 2Sicurotrone Trieste, Bascovizia, Italy.

Silicon nitride layers with a thickness of ≤2 nm grown on Si(111) have been deposited by plasma-enhanced chemical vapor deposition (PECVD) techniques employing microscopy, spectroscopy, and diffraction techniques. The films were grown by reactive nitrogen deposition from rfd and ECR plasma sources at substrate temperatures ranging from 700°C to 1050°C. From scanning tunneling microscopy (STM) measurements at sub-monolayer coverages, the formation of a well-ordered interface is observed. The presence of the surface reconstruction up to the saturation thickness, as observed by low-energy electron diffraction (LEED) at high temperatures. This is confirmed by the investigation of the film morphology by in-situ TEM and ex-situ AFM. At lower temperatures, the films are hydrogenated and almost atomically smooth. In addition, such SiN layers have been used as buffer layers for subsequent growth of GaN films. First STM and x-ray scattering results are presented.

SESSION Y11: Processing
Chair: Suzanne Mohney
Friday, December 5, 2003
Room 313 (Hynes)

8:30 AM Y11.1
Gate leakage suppression and contact engineering in nitride heterostructures. Yah-Heng Wu, 1 Madhusudan Singh, 1 Jaspreet Singh and Umesh K Mishra 2, 1Electrical Engineering and Computer Science, University of Michigan, Ann Arbor, Michigan, 2Electrical and Computer Engineering, University of California, Santa Barbara, California.

In conventional semiconductor junctions between metals and semiconductors, the properties of the junction can only be altered by doping once a metal and semiconductor are chosen. In polar semiconductor devices, the interactions between layers can be produced, the junction's properties can be altered to range from Ohmic to tunneling by block changes in design. In this work, we will present results of a self consistent model of current-voltage characteristics in a metal-polar semiconductor junctions. It is known that due to a very strong piezoelectric effect and large spontaneous polarization in nitrides, fixed charge densities as high as 5 x 10^{13} cm^{-2} can exist at the interface, as a result of such a large spontaneous polarization exists in ferroelectric materials. These charges can cause very large band bending and possibly induce two dimensional electron or hole gas. To study nitride and ferroelectric junctions and consider the effect of adding hetero layers, we have developed a new model, the drift-diffusion charge-control model, which is an improvement on our earlier charge control model. It addresses charge control as well as transport through tunneling and drift-diffusion.

This model is applied to examine properties of three classes of junctions that are important in devices: i) metal/GaAlN/GaN structures that are used in nitride heterojunction field effect transistors; ii) metal/GaAlN/GaN structures for potential applications in very small gate devices to suppress gate tunneling current; iii) metal/polar insulator/GaN/AlGaN junction with practical application for low source resistance regions. The physical parameters used for high-κ dielectrics and polarization charges reflect values measured in ferroelectric hexagonal GaN powders with high luminescence efficiency without the need for post-growth treatment. The material has been obtained by a complete reaction between high purity gallium metal (99.999%) and ultra-high purity ammonia (99.9999%) in a horizontal quartz tube reactor at 1000 °C. The powders produced in this reactor consist of light grey micro-crystals with wurtzite structure. Elemental analysis indicates that the powders obtained by this method have a high nitrogen concentration (more than stoichiometric GaN, 16.7%).

Powder X-ray diffraction demonstrates that the material has a high purity and single crystalline structure. Electron microscopy shows that the powder consists of at least two kinds of particles, small sized platelets and large sized needles. The GaN powders obtained by this method produce high efficiency ultra-violet luminescence around 370 nm (3.3 eV, near band-edge emission) when they are excited by accelerated electrons (cathodoluminescence) or by photons (photoluminescence) at room temperature. [1] W.C. Johnson, J.B. Parace, and M.C. Crew, J. Phys. Chem., 36, 2651 (1932).

8:45 AM Y11.2
Formation of thin GaN microdisks supported by InGaN pedestals using photoelectrochemical etching. Elinor D. Hsu, Andreas Sturm, Rajeev Sharma, Susji Nakamura, Steve DenBaars and Evelyn L. Hu, 1Materials Dept., UCSB, Santa Barbara, California, 2Electrical and Computer Engineering Dept., UCSB, Santa Barbara, California.

Microdisks have been used in GaAs and InP materials to form extremely high quality resonators for optical devices, ultimately resulting in low-threshold lasing. A microdisk is a thin semiconductor disk surrounded by a laser index material. Through internal reflection, the circular geometry of the disk gives rise to low loss whispering gallery modes (WGMs) which propagate along the periphery of the disk. The GaN material system is well-suited for the microdisk structure because other mirror geometries such as clamped mirrors and several period epitaxial mirrors can be problematic. The difficulty in forming a GaN microdisk is the ability to optically isolate the disk. In other material systems optical isolation of the WGMs is generally achieved by using a selective wet etch to etch-off the underlying substrate, the disk, forming a pedestal. Because GaN-based materials do not have a simple wet etch, we must use another method to optically isolate the disk. We have chosen to use InGaN/GaN pedestal selective photoelectrochemical etching (SPECE). In this technique a GaN mirror is immersed in an electrolyte solution and exposed to filtered light from a Xe lamp. The filter allows photons with energy less than the bandgap of GaN to pass, generating electron and holes in the InGaN pedestal. These photoelectrolysis effects drive the photo-induced etch. In previous studies, we have used a single composition, 100 nm In_{0.12}Ga_{0.88}N sacrificial layer with KOH as the electrolyte to lift-off 1 micron thick GaN microdisks. Because of limited selectivity and non-optimized etch conditions, the undercut surface was so rough that it was necessary to use chemical-mechanical polish to smooth the disk following lift-off. In the latest research, we have explored several different PEC conditions and have designed different epitaxial structures for the sacrificial layer. We have found that we can significantly reduce the roughness of the undercut by (1) increasing the InGaN/GaN selectivity using HCl as the electrolyte and (2) more uniformly covering the holes using an 10 nm GaN/In_{0.12}Ga_{0.88}N/In_{0.2}Ga_{0.8}N/In_{0.2}Ga_{0.8}N/In_{0.2}Ga_{0.8}N superlattice. We have fabricated 120 nm thick GaN microdisks which do not require lift-off and polishing, but actually sit upon 220 nm InGaN pedestals. This study explores the optical emission of the GaN microdisks.

9:00 AM Y11.3
Vanadium-Based Ohmic Contacts to High Al Fraction AlGaN. Jianming D. Wang, 1 Sammy H. Wang 2, Russell P. Dupper, Utsyn Chehnev 2 and Suzanne E. Mohney 2, 1Department of Materials Science and Engineering, The Pennsylvania State University, University Park, Pennsylvania; 2University of Texas, Austin, Texas.

As group III nitride emitters are developed for operation at shorter wavelength, there is a need for Ohmic contacts to n-type AlGaN with
higher Al fractions. For n-Al$_2$O$_3$GaN$_x$N and n-Al$_2$O$_3$GaN$_x$N, we previously compared Ti/Al/Pt/Pt/Au ohmic contacts (similar to those used for n-GaN in [12]) to the HREM contacts. In both cases, the optimized contact with V as the first layer provided a lower specific contact resistance and required lower annealing temperatures than did the optimized contact with Ti as the first layer. On n-Al$_2$O$_3$GaN$_x$N, a specific contact resistance of 4 × 10$^{-5}$ Ωcm$^2$ was achieved. In this presentation, we describe TEM and AFM characterization of the V/Al/Pt/Au contact as well as successful efforts to reduce the specific contact resistance and improve upon the specific contact resistance and the surface morphology of our contacts. We learned that the interface between the annealed V/Al/Pt/Au contact and Al$_2$O$_3$GaN$_x$N is planar and that consumption of the semiconductor material is minimal. However, the surface of the contact is not very smooth, with an RMS roughness of 110 nm measured by AFM. By replacing the Pt layer with Pd and optimizing the layer thicknesses, we were able to reproducibly reduce the specific contact resistance by an order of magnitude, providing an average specific contact resistance of 0.35 × 10$^{-5}$ Ωcm$^2$. TEM images indicate that replacing the Pt with V also allows us to reduce the specific contact resistance and improve upon the surface morphology of the contacts. Further characterization of the contacts by TEM is underway to provide a comparison between the metal/semiconductor interfaces of the contacts in an effort to understand why some of the metallization schemes provide a lower contact resistance than others.

9:15 AM Y11.4 Reduction of the p-type contact resistance in GaN-based laser diodes. Andreas Weimann, Alfred Leff, Andreas Leher, Stephan Müller, Volker Heese, Georg Bremer, Volker Baehrme, OS T2, OSLAM Opto Semiconductors, Regensburg, Germany.

For GaN-based laser diodes there will be various applications in near future like in telecommunication, laser scanners and projectors. At OSLAM Opto Semiconductors, blue laser diodes are developed since 1998, which led to the first continuous wave operation in Europe in 2001. The [Al,Ga,In,Ga]N-compound semiconductor layers are grown by MOVPE on InGaN single substrates. The contact technology is the key influence on the laser diode lifetime of various groups leads to the conclusion that the most limiting factors for the laser diode lifetime are the high dislocation density as well as the heat generation by electrical losses. In the latter case, the p-type contact resistance plays an important role because of its large contribution to the operation voltage. In this work, we present results of systematic investigations concerning the impact of technological parameters on the specific contact resistance including the choice of the contact metal with regard to its work function, the p-GaN surface preparation, hydrogen incorporation by a typical PECVD process as well as the dependence of the contact resistance on the Mg-doping concentration. The results of these investigations were implemented in the p-type contact technology of laser diodes. By those changes, the operation voltage of the laser diodes was lowered from 3.3 V to 6 V. The reduction of the operation voltage and thus the operation power was an essential contribution to the increase of the laser diode lifetime to the current best value of 148 h.

9:30 AM Y11.5 Influence of metal thickness to sensivity of Pt/GaN Schottky diodes for Gas sensing applications, Vignyb Tinh1, Magdiedin Ali2, Volker Cimina3,4, Peter Sandvik1, Jeff Fedrosc1, Oliver Ambacher5 and Daniele Merfeld1, 5 GE Global Research, Niskayuna, New York, 6Center of Molecular and Nanotechnologies, Technical University Ilmenau, Ilmenau, Thuringia, Germany.

A hydrogen gas sensor based on a Pt/GaN Schottky diode structure was fabricated and the behavior of the device to hydrogen was studied. Pt/GaN Schottky diodes were fabricated on Si doped GaN layer (ND = 10$^{11}$ cm$^{-2}$) grown with a thickness of 3 μm on sapphire substrates. Ohmic contacts were processed by evaporating Ti/Al metal stack at 800°C in nitrogen atmosphere. Three different sets of Schottky diodes were fabricated each with 80 Å, 240 Å and 400 Å of Platinum as top contacts evaporated using e-beam evaporator. All three sets of devices were passivated using silicon dioxide. Gold bond pads were evaporated on the Ohmic and Schottky electrodes. The devices were then wire bonded to a 16 pin package. An external heating element was present in the package to which the device was mounted on in order to increase the temperature of the device up to 300°C. The current-voltage performance of a 0.35 x 0.25 mm$^2$ Schottky diode was tested in 1% volume, hydrogen gas diluted by nitrogen for gas sensor applications. The devices were operated in constant current mode (5 mA constant current) in a forward bias condition. The temperature was controlled by applying a constant voltage to the external heater and measuring the temperature using a thermocouple. The change in voltage of the diode at a fixed current was monitored with the diode exposed to hydrogen in air at different temperatures. The response, as measured by the change in voltage increased as the thickness of the Schottky metal contact decreased at any given temperature. For example at 300°C, the exposure of the Pt/GaN Schottky diode at 80 Å, 240 Å and 400 Å Schottky metal contacts caused a response of 238 mV, 340 mV and 185 mV, respectively. Furthermore, the sensitivity increased with increasing temperature for all Pt thickness starting from room temperature to 300°C, beyond which the specific contact resistance of the 240 Å Schottky contact device. The sensitivity of the 80 Å Schottky contact devices continues to increase up to 365°C, the temperature to which these measurements were performed. The trend of increasing response with increasing temperature was observed in 0.3 x 10$^{-5}$ - 1 x 10$^{-5}$ m$^2$ size Schottky diodes. The increment in sensitivity to decrease in thickness points to the dissociation of molecular hydrogen on the surface due to the diffusion of atomic hydrogen through the bulk plasma and the adsorption of hydrogen to the surface as a possible mechanism of sensing by Schottky diodes [1]. Very likely, the thinner metal facilitates the easier diffusion of atomic hydrogen through the bulk plasma causing a higher sensitivity. Reference: [1] J. Schilling, F. Herrmann, L. Stumpf, G. Dellinger, Appl. Phys. Lett. 80, 1222 (2002).

9:45 AM Y11.6 Low resistance ohmic contacts to AlGaN/GaN heterostructure field effect transistors. Deepak Sevanthas, Anur Teshfeyysa, Vigan Kumar and Hasmini Adesida, Electrical and Computer Engineering, University of Illinois, Urbana, Illinois.

Wide bandgap GaN-based heterostructure semiconductors are of interest in the area of high frequency, high temperature and high power electronic devices. High quality ohmic contacts with low contact resistance (< 0.5 Ωcm$^2$) are required to fabricate such high performance devices. Ti/Al/Ti/Au, Ti/Al/Ni/Au and Ti/Al/Pt/Au metallization schemes are the standard approach to achieve low resistance ohmic contacts on AlGaN/GaN HFETs. In this work, we compare the ohmic characteristics of Ti/Al/Mo/Au and V/Al/Mo/Au and Mo/Al/Mo/Au metallization schemes on AlGaN/GaN HFETs. The ohmic performance of the contacts is characterized based on transfer characteristic (I-V) and current-voltage (I-V) measurements. The variation of contact resistance and specific contact resistance of the ohmic contacts has been studied as function of the anneal temperature for the three metallization schemes. From the TLM measurements, Ti/Al/Mo/Au ohmic contacts exhibit low contact resistance with a value of about 0.25 Ωμm when annealed at 850°C. V/Al/Mo/Au ohmic contacts exhibit high surface roughness and poor edge purity when annealed at high temperatures with a contact resistance of 0.35 Ωμm and Mo/Al/Mo/Au ohmic contacts are more stable with a contact resistance of 0.27 Ωμm. Results on our investigation of the long-term thermal stability of these contacts at higher temperatures will be presented. The surface morphology of the three types of ohmic contacts are characterized using atomic force microscopy measurements. The intermetallic reactions occurring during ohmic contact formation are being studied using Auger electron spectroscopy (AES). Ohmic contact formation mechanisms for AlGaN/GaN HFETs will be discussed.

10:30 AM Y11.7 Ohmic contact to n-type and p-type (Al)GaN semiconductors. Hasmini Adesida, Deepak Sevanthas and Hyun-Kyong Cho, Department of Electrical and Computer Engineering, University of Illinois Urbana-Champaign, Urbana, Illinois.

The direct bandgap of GaN-based semiconductors have made them attractive materials for the realization of a wide range of optoelectronic devices. Examples of devices that are either commercially available or demonstrated in laboratory include short wavelength light emitting diodes (LEDs), solar blind detectors, and laser diodes which have applications in white light illumination, bio-chemical agent sensing, solar UV detection, missile detection, flame and heat sensing, ozone monitoring, and remote sensing. Materials growth and device processing are still critical issues in terms of obtaining highly efficient GaN-based optoelectronic devices. The realization of highly reliable, thermally stable, low resistance ohmic contacts to both n-type and p-type GaN-based semiconductors is essential. To date, the formation of contacts to AlGaN with high Al concentration remain a challenge for various reasons. In this paper, we will present our work on ohmic contact formation to both n-type and p-type AlGaN of various Al concentrations. Results on n-type contact formation using Ti/Al/Mo/Au and other metallization schemes will be presented. Contact formation to p-type AlGaN using Pt-based metallization schemes will be presented. Issues of the bond stability of these contacts will be discussed. The efficacy of various surface treatment schemes for GaN and AlGaN to improve the ohmic
performance of the contacts will be discussed. Comprehensive studies are being performed to compare the effects of various surface treatments that include h-BN and AlGaN on the electrical and material characteristics of p-GaN and n-AlGaN semiconductors. Further, the mechanism of formation of Ohmic contacts in these semiconductors will be discussed. This work was supported by DARPA and ONR grants.

11:00 AM Y11.8
GaN Microstructures Formed by Polarity-Selective Chemical Etching. Arvind Thadhani, Hock M. Ng, Wolfgang Parz and Nils G. Weimann; Bell Laboratories, Murray Hill, New Jersey.

The ability to fabricate microstructures such as photonic crystals is of importance because these structures enable us to control and manipulate the behavior of light. As such, it is desirable to fabricate GaN microstructures because of the material's wide window of transparency from 355 nm to 1.36 μm. However, the strength of the GaN lattice (8.05 eV/atom) results in the material being chemically very stable. Thus, the focus of research for attaining removable etch rates has been on dry etching techniques such as reactive ion etching, inductively coupled plasma etching and chemically-assisted ion beam etching. However, mask erosion during the dry etching process results in slanted sidewalls for etch depths greater than 1 micron. In this work, we present 1D and 2D GaN microstructures fabricated by polarity-selective chemical etching. This fabrication technique involves growing a pattern of GaN and N-GaN regions by plasma-assisted molecular beam epitaxy and then subjecting the sample to a KOH solution. The process does not require an etch mask as the KOH selectively etches the N-polar regions, thus forming the GaN microstructures with improved sidewalls of up to 35 degrees compared to GaN achieved with very smooth vertical sidewalls. The particular GaN microstructures that will be presented are a 1-D grating and a 2-D lattice of hexagonal holes.

11:15 AM Y11.9
Device and Process Optimization of AlGaN/GaN Current Aperture Vertical Electron Transistors (CAVETs) Fabricated by Photoelectrochemical wet etching. Yao Gao, Ilia Ben-Yacov, Umesh Mishra, Steven DenBlaar and Evelyn Hu, 1, 2
1Materials Department, University of California, Santa Barbara, Santa Barbara, California; 2Electrical and Computer Engineering Department, University of California, Santa Barbara, Santa Barbara, California.

We have previously reported that fabrication of AlGaN/GaN Current Aperture Vertical Electron Transistors (CAVETs) formed by photolithography and electron beam lithography. The current aperture in our CAVETs was formed by a recessed-selective etching of a thin (60 nm) InGaN sacrificial layer incorporated into the device structure. The initial device results showed a high voltage offset around 24 V and current density around 0.3 A/mm [1]. The offset was related to the large electron barrier arising from the built-in piezoelectric field in the unintentionally doped, strained InGaN layer. Dopant InGaN layers grown on GaN without the piezoelectric field and with the electron barrier, however this change in the material composition dramatically degraded the smoothness and selectivity of the KOH etchant and resulted in deep p-type columns. A possible effect of device structure design and process parameter development is a new CAVET device having significantly reduced offset (0.07 V), with Imax = 0.32 A/mm and gm = 67 mS/mm. The material structure was modified in response to the need for higher field extraction and to ensure a hole confinement to enable efficient and selective PEC etching. The process optimization involved a variety of etchant (KOH, HCl, H2SO4/H2O2) and etching conditions. We will discuss both the device and process optimization, as well as the RF performance of this CAVET. [1] Y. Gao, A. R. Stock, I. Ben-Yacov, U. K. Mishra, S. P. DenBlaar, E. H. Lu, AlGaN/GaN Current Aperture Vertical Electron Transistors (CAVETs) fabricated by photoelectrochemical wet etching, published in Electronics Letters, vol 39(1), 188-189 (2003)

11:30 AM Y11.10
LaserInduced Facette Degradation Study. Ulrich Thoden van Veluw, Thomas C. Chen, Volker Kuenzler, Alfred LeF and Volker Haegele, 1, 2
1NWF II - Physik, Regensburg University, Regensburg, Germany; 2Osrn Opto Semiconductors GmbH, Regensburg, Germany.

We study the ageing behaviour of GaN gain guided laser diodes on Si substrates with cleaned facets and reflective coatings on one, one, or both facets. This allows us to demonstrate that in addition to volume effects there is a strong correlation of the laser output power to the laser degradation. We observe that for the uncoated laser diodes the threshold current density is increasing considerably faster compared to laser diodes with mirror coatings. Also for the coated laser diodes with increasing threshold current density the shunting gain is decreasing. This is consistent with an increase in absorption at the laser facet. Degradation is observed during operation but not during storage at ambient conditions and thus expected to be photon or current induced. Judging from ongoing aged laser studies we tend to believe wet chemical processes on the electrical and material characteristics of n-GaN and p-AlGaN semiconductors. Further, the mechanism of formation of Ohmic contacts in these semiconductors will be discussed. This work was supported by DARPA and ONR grants.

11:45 AM Y11.11
Low-Resistance, High Yield Ohmic Contact to GaN-Based HEMTs. Karen S. Boush1, B. Breb, M. Regan, B. Buttrn and U. Mishra2, 3Materials and Devices, Rockwell Scientific Company, Thousand Oaks, California; 2University of California Santa Barbara, Santa Barbara, California.

Low-resistance ohmic contacts are key to high performance GaN HEMTs for microwave and mm-wave applications. State-of-the-art Ti-based contacts, which are widely used in GaN HEMT processes, have Rc < 0.5 Ω·mm, and have resulted in record device performance. However, this contacts suffer from poor edge definition and surface roughness due to non-uniform alloying during contact anneal. This results in a compromise of performance at the expense of device yield, since the contact roughness forces the placement of the gate far from the source. A low-resistance Ti-based ohmic contact with improved edge definition and surface roughness was achieved by using a KOH solution etch followed by a hydrogen anneal. The resulting contact has a smooth surface and a high edge-roughness after alloying. This feature leads to a high device yield (> 85%) over a 2-inch wafer, for devices with gate-to-source spacing of 0.45 micron. An alloying process window, which is largely insensitive to wafer temperature and time, exists for this contact scheme making it favorable from the viewpoint of reproducibility. However, the contact resistance is found to be very sensitive to the surface condition prior to metal deposition. A short oxide-pre by an IC dry-etch tool, prior to deposition of the ohmic metal, resulted in a reproducible high quality ohmic contact. Our process results in a very low contact resistance of 0.5 Ω·mm over multiple lots of 2-inch wafers from different vendors. Additionally, breakdown voltages in excess of 100 V have been obtained on devices with 0.3 micron long gates as a result of the sharp contact definition. An An/Fmax of 80/120 GHz, and a Gm of 300 mS/mm have also been measured on the same devices, making the Ti-based ohmic contact suitable for implementation in RF device. We will report on the results and experimental conditions studied to develop this ohmic contact scheme. We will also present wafer-level device parameter uniformity data using this contact scheme.

SESSION Y12.1
InN-Mixed Nitrides
Chair: Hock Min Ng
Friday Afternoon, December 5, 2008
Room 312 (Hyne)

1:30 PM Y12.1
Band-Gap Energy and Physical Properties of InN Grown by RF-Molecular Beam Epitaxy. Yasushi Narishige1, Yoshiki Sato1, Tomohiro Yamanuchi1, Bunie Matsuda1, Tatsuo Araki1, Akira Suzuki2, Hiroshi Harima1 and Takao Miyajima1, 2Department of Photonics, Ritsumeikan University, Kusatsu, Japan; 3Research Organization of Science and Engineering, Ritsumeikan University, Kusatsu, Japan; 4Department of Electronics and Information Science, Kyoto Institute of Technology, Kyoto, Japan; 5Core Technology Development Center, Core Technology & Network Company, Sony Corporation, Atsugi, Japan.

Band-gap energy of InN has long been believed to be 1.9 eV after it has been reported from optical absorption experiments using polycrystalline InN and InGaN. Recent studies on MOCVD and RF-MBE growth of InN enabled us to obtain high-quality single crystalline InN and good electrical properties such as room temperature electron mobility over 2000 cm²/Vs and residual carrier concentration close to 3x10¹⁷/cm² were reported [1]. Very recent studies on PL, optical absorption and photo-reflectance measurements using high-quality InN have demonstrated that the fundamental band-gap of single crystalline InN should be 0.7-0.8 eV [2]. In this presentation, we review recent studies on high-quality InN and InGaN grown by RF-MBE on sapphire. To obtain high-quality InN, the following growth conditions were found to be essential, which were (1) n-type doping of the sapphire substrate, (2) two-step growth, and (3) precise control of V/H ratio and (4) selection of optimum growth temperature. Characterization studies using XRD, TEM, EXAFS and Raman scattering have clearly demonstrated that InN grown in this
study have ideal hexagonal wurtzite structure. The full widths at half maximum (FWHMs) of $\omega$ mode XRD, $2\theta$ mode XRD and $E_2$(high) mode peak in the Raman scattering of the samples were as small as 20.6, 28.9, and 3.2°, respectively. The carrier concentration and room temperature mobility were $4.8 \times 10^{13}$ cm$^{-2}$ and 1200 cm$^2$/Vs. InGaN films with full compositional range were grown and the PL spectra of the PL and CL studies both on these well-characterized high-quality InN and full composition InGaN films have clearly demonstrated that bandgap energy of InN should be less than 0.75 eV, approximately 0.7 eV at room temperature in InN. The determination of the bandgap of InN, however, further reduction in residual carrier concentration should be needed. Possible application fields of narrow band-gap InN and its compatibility with Si substrates should also be included in this presentation. [1] H. Lu et al, MRS Symposium Proceedings 743, L4.10 (2003). [2] V. V. Davydov et al, J. Appl. Phys. Lett. 80, 2367 (2002). This work was supported by MEXT, Grant-in-Aid for Scientific Research (B) #18340131, Academic Frontier Project and the 21st Century COE Program.

20:00 PM 1Y12.2
Epitaxial Growth of High Quality InN Films With PLD.
Hiroshi Fukuji1, Tasuku Honke1, Tsubasa Ohno1, and Masa furu Oshima1
1Department of Applied Chemistry, The University of Tokyo, Komaba, Tokyo, Japan., 2Kawasewa Academy of Science and Technology, Kawasaki, Kanagawa, Japan.

We have grown InN films on sapphire (0001) and YSZ (111) by pulsed laser deposition (PLD) for the first time and investigated the effect of the substrate on the structural properties of the InN films with RHEED, HRXRD, XTEM, and AFM. Growth of InN is performed in a PLD apparatus with a background pressure of 1.0(1)×10$^{-6}$ Torr. RHEED patterns for YSZ and InN on both YSZ and YSZ are sharp streaks, which indicates that high quality InN grow with flat surfaces. Careful interpretation of RHEED patterns led us to conclude that InN (0001) grows on both substrates and in the plane epitaxial relationships for YSZ and YSZ are InN [11-20] // YSZ [11-20] and InN [11-20] // YSZ [11-20]. The lattice mismatch estimated from these in-plane alignments for YSZ and YSZ are 29% and 23%, respectively. Drastic reduction in the lattice mismatch by the use of YSZ substrates improved both structural and electrical properties of the InN films. Although it was well known that the reduction in the twist angle of InN is quite difficult, the FWHM values of the 20-24 X-ray rocking curves for InN grown on sapphire and YSZ are 24 and 20.8 arcmin, respectively. XTEM observation revealed that the threading dislocation density for the InN grown on YSZ is quite low (10$^{4}$ cm$^{-2}$). These results indicate that the use of PLD and YSZ (111) substrates is promising for the epitaxial growth of high quality InN films.

21:15 PM 1Y12.3
Optical and Microstructural Characteristics of InN on (0001) Sapphire and (001) YSZ by Plasma-Assisted Molecular Beam Epitaxy.
C. E. Kendall1, T. E. Lee1, W. J. Rees2, V. J Kennedy3, T. M. Durbin1
1Electrical & Computer Engineering, University of Canterbury, Christchurch, New Zealand, 2Department of Physics, University of Canterbury, Christchurch, New Zealand, 3Institute of Geological & Nuclear Sciences, Ltd., Lower Hutt, New Zealand.

Determination of the optical properties of InN is relevant for understanding the detailed behaviour of InGaN alloys. Recent reports that the bandgap energy may be much lower than the commonly quoted value of 1.89 eV—possibly as low as 0.6 eV—has led to renewed interest, however, as this would enable a new range of applications for the material, such as high-efficiency multijunction photovoltaic devices. If true, it would also impact interpretation of indium-rich regions (such as self-assembling quantum dot like structures) within InGaN layers. We have investigated the optical and structural properties of both (0001) InN and (001) YSZ substrates using a plasma-assisted molecular beam epitaxy (PAMBE) technique. Film thickness is typically on the order of 0.8 nm, corresponding to a growth rate of 100 nm/hr. Single crystal films are obtained for substrate temperatures in the range of 350-550°C, as confirmed by in-situ reflection high-energy electron diffraction (RHEED). The only photoluminescence features are observed between 0.7 and 0.8 eV, and have linewidths of approximately 60 to 150 meV, depending on conditions. The absence of photoluminescence features in the visible region can be observed above the limits determined by laser scattering. The temperature of the sample is increased to 30K to observe a few peaks, which is characteristic of high quality material as noted by other groups, and reduces in intensity until becoming too weak to detect above 150 K. The opposite behavior is observed for a film grown on [001] YSZ however, where a distinct red shift is observed with increasing temperature, as would be expected from a band-edge-related feature. An increase in intensity with increasing temperature is also observed in the same sample. For films grown on sapphire, two distinct regimes are observed. The first regime is characterised by spotty growth patterns, and a surface morphology consisting of very flat interconnecting platelets exhibiting distinct hexagonal symmetry. The hexagonal features, having a size of approximately 100 nm, are well aligned across the film. The second regime, which is obtained for interfacial layers, where the RHEED features are observed. AFM analysis of the surface shows distinct isolated columnar features with hexagonal symmetry and a width of approximately 1 micron. Interestingly, photoluminescence is observed from these films as well as from XRD RHEED determination. The time scale at which these films are cooled shows the presence of a thin (~40 nm) layer of indium oxynitride at the surface of all films, with an essentially stoichiometric and oxygen-free (to within measurement resolution) InN layer beneath. Nucleation of InN on YSZ is initially cubic, but the film quality rapidly deteriorates. AFM of the final film surface is suggestive of features having cubic rather than hexagonal symmetry, although the roughness is comparable to that observed in these films is comparable to that observed in these films. Luminance from these films is comparable to that of films grown on sapphire.

2:30 PM 1Y12.4
Microstructure of InN Films Grown on GaN by Metal-Organic Vapor Phase Epitaxy.
Rong Liu1, S Srinivasan1, F A Ponce2, H Amarni3 and I Akasaka4
1Department of Physics and Astronomy, Arizona State University, Tempe, Arizona, 2Department of Materials Science and Engineering, Meijo University, Nagaoy, Japan.

The bandgap of InN was thought to be 1.7 eV, but recent results have shown that it may be a much lower value. Little work has been done to determine the microstructure of InN films deposited on GaN, which effects the optical properties. In this work, we studied a set of InN samples grown under different conditions, using XRD and TEM. Two InN films were deposited on GaN templates using metal-organic vapor phase epitaxy (MOVPE) system. The first sample has a background carrier concentration of 5.8 x 10$^{18}$ cm$^{-3}$ and an absorption edge of ~0.8 eV, while the values for the latter are 7.8 x 10$^{19}$ cm$^{-3}$ and ~1.1 eV. XRD analysis indicates that the c-lattice parameter of the sample grown at 500 degree Celsius is larger (7.01 vs. 7.66 angstroms), and closer to the calculated value of InN powder diffraction. TEM images show significant difference between the microstructure of the samples. The sample grown at high temperature produces bulk crystalline quality material, with mostly one-dimensional threading dislocations. The lower temperature growth is dominated by two-dimensional grain boundaries. This difference in the well-defined InN/GaN Interface for both samples. It is evident that the lattice mismatch strain is relaxed. InN lattice constants on the basal plane are estimated from lattice images to be 3.55 and 3.33 angstroms for growth at 500 and 450 degree Celsius, respectively. We find that the improved crystalline quality of InN grown at higher temperature is associated with a larger unit cell, and a lower background carrier density. With this work, we have shown that the crystalline quality of the material strongly affects the optical properties, so it is important that microstructure is considered when determining the band-gap of InN.

2:45 PM 1Y12.5
Temperature Dependence of the Optical Properties for InN Films Grown By RF-MBE.
Yoshitaka Inahashi1,2,3, Hirohito Masuyama1, Ke Xu1, Masaoki Yoshitani1, Wataru Terasawa1, Nicki Hashimoto1, Songke Che1,2,3, and Akihiko Yoshikawa1,2,3
1Electronics and Mechanical Engineering, Chiba University, Chiba, Japan, 2II-RCEST, Chiba, Japan, 3VIL, Chiba University, Chiba, Japan.

Recently the bandgap energy Eg of InN was proved to be less than 1 eV. Many researchers have started the study on InN for the sake of application to ultrafast optical communication devices. However, several basic physical parameters are not yet determined. Although a few values of the effective electron mass (me*) were reported, there is no direct measurement by optical methods. In order to account for the TO phonon and LO phonon-plasmon coupling mode frequencies in a wide wavenumber range 350-8000 cm$^{-1}$, using thick films (several micrometers). Eg for the intrinsic crystal was reported as 0.96(6) eV. Temperature dependence of the PL peak energy was reported to decrease with decrease in temperature in contrast to novel semiconductors. However there is no report on the dependence of the transmission spectrum. We measured the optical reflectance and transmission spectra in a wide temperature range of 5-300K for a single crystal grown on YSZ. The thickness of 1.7-5.5 μm and carrier concentration Ne of 1.5-1×10$^{18}$ cm$^{-3}$. We estimated me* of the intrinsic crystal in 0.977 [eV·Å] and determined the parameter of several materials for numerical calculation. Since the plasma edge is constant with the temperature decrease, a band of impurity or defect is formed. Thus the estimated Eg from absorption edge is probably smaller than the actual one. The absorption edge energy increases with the decrease in temperature to 50 K, below which it decreases. From 50 to 5 K the decrease in the


3:30 PM Y19G

Growth of Non-polar a-plane and Cubic InN on r-plane Sapphire by Molecular Beam Epitaxy, Hai Lu$^1$, William J. Schaaf$^2$, Lester F. Eastman$^3$, Volker Cimalla$^4$, Oliver Ambacher$^5$, J. Wu$^6$ and W. Walkiewicz$^7$, $^1$Electrical and Computer Engineering, Cornell University, Ithaca, New York, $^2$Center for Micro- and Nanotechnologies, Technical University Ilmenau, Ilmenau, Germany; $^3$Materials Sciences Division, Lawrence Berkeley National Laboratory, Berkeley, California.

Growth of non-polar III-nitrides has been an important subject recently due to its potential improvement on the efficiency of III-nitride-based opto-electronic devices. Despite of the intensively studied non-polar GaN and GaN-based heterostructures, there are very few reports on epitaxial growth of non-polar InN, which is also an important component of the III-nitride system. Moreover, recent this material has received much attention due to the discovery of its narrow band gap around 0.7 eV. This discovery greatly extends the range of emission spectrum of III-nitrides, and thus makes it possible to fabricate III-nitride-based light emitter over a broader wavelength range from infrared to ultraviolet. In this study, we first report heteroepitaxial growth of non-polar InN on r-plane sapphire substrates using plasma-assisted molecular beam epitaxy. It is found that when a GaN buffer is used, the following InN film appears to be non-polar (11 20) plane which follows the r-plane InN bulk. Optical absorption and photoluminescence measurements of this material show that InN has a fundamental bandgap of about 0.7 eV which is also seen for growth on r-plane sapphire. The room temperature Hall mobility of this non-polar InN is around 2000 cm$^2$/V·s with a concentration around 6x10$^{18}$ cm$^{-3}$. Meanwhile, if InN film is directly deposited on r-plane sapphire without any buffer, the InN layer is found to consist of a predominant zincblende (cubic) structure along with a fraction of the wurtzite (hexagonal) plane which content increases with increasing growth. A model is proposed to explain this unusual epitaxial relationship in which a metastable cubic phase forms on a noncubic substrate while the wurtzite phase arises as the special case of growing in the cubic structure.

3:45 PM Y19J

Optical and Electrical Properties of Non-Degenerate and Highly Degenerate InN Films, Dart D. Haskins$^1$, Judgish S. Thakur$^2$, Yuan M. Naik$^2$, Gregory W. Auner$^1$, Renu Naik$^2$, Lowell E. Wenger$^1$, Hai Lu$^3$ and William J. Schaaf$^4$, $^1$Department of Physics and Astronomy, Wayne State University, Detroit, Michigan; $^2$Department of Electrical and Computer Engineering, Wayne State University, Detroit, Michigan; $^3$Materials Sciences Division, Lawrence Berkeley National Laboratory, Berkeley, California; $^4$Department of Electrical and Computer Engineering, Cornell University, Ithaca, New York.

The influence of electron carrier concentration (not intentionally doped), $n$, on the optical and electrical properties of two different InN films has been investigated. Sample A is an InN film, 2 μm thick grown on a GaN buffer layer on [0001] sapphire substrate by molecular beam epitaxy, with $n \sim 7.5 \times 10^{17}$ cm$^{-3}$ and a mobility of $\sim 1488$ cm$^2$/V·s as measured by Hall effect at room temperature. Sample B is an InN film, 0.5 μm thick grown by plasma source molecular beam epitaxy on [0001] sapphire, with $n \sim 3 \times 10^{18}$ cm$^{-3}$ and a mobility of $\sim 55$ cm$^2$/V·s. Useful crystalline quality of the former film was confirmed by both x-ray diffraction and Raman scattering. Analyses of optical absorption spectra of both films, determined using transmission and reflection data, show an optical bandgap absorption coefficient, $\alpha$, for sample A and B of 45 and 1.5 eV for sample B. The latter sample also shows a plasma absorption peak around 0.5 eV due to a high carrier concentration. It has been recently shown that the observed high values for the InN bandgap is due to a Moss-Burstein shift in highly degenerate InN films. Temperature dependent (5-350 K) measurements of the extrinsic electrical resistivity clearly show a semiconducting behavior for sample A with an activation energy of $\sim 2$ meV. On the other hand, a metallic type of conduction is observed in growing films with low InN at temperatures lower than 300 K.

The recent discovery of the fundamental bandgap of InN near 0.7 eV has attracted renewed attention to the properties of InN and In-rich nitride alloys. We have studied the hydrostatic pressure dependence of the fundamental bandgap of InN, In-rich In$_{1-x}$Ga$_x$N (0 < x < 0.5), and In$_{0.5}$Al$_{0.5}$N (x = 0.25) alloy by measuring the optical absorption spectra in diamond anvil cells. The pressure coefficient was determined to be $3.0 \pm 0.1$ meV/kbar for InN. The values of the pressure coefficients of the In-rich alloys are very close to that of InN, which results agree with theoretical predictions. Together with previous experimental results [pressure coefficient = $4.6 \pm 0.2$ meV/kbar for GaN [1] and $5.6 \pm 0.2$ meV/kbar for AlN [2]], our data indicate that the pressure coefficient of group-III nitrides has only a weak dependence on the alloy composition. The small pressure coefficient of group-III nitrides as compared to other III-V compounds can be attributed to their high ionization, which also explains the decrease of the pressure coefficient with increasing electron number of the nitrides. We also found that the pressure coefficient of the photoluminescence peak energy of InN amounts to 0.6 to 0.9 meV/kbar and is much smaller than the pressure coefficient of the absorption edge energy. This result suggests that highly localized levels could be involved in the radiative recombination process. [1] S. Shin, W. Walkiewicz, E. E. Haller, B. D. Little, J. J. Song, M. D. McCluskey, N. M. Johnson, Z. C. Feng, M. Schurman, and R. A. Scott, J. Appl. Phys. 84, 4452 (1998).

In displacement AlKα, AlKβ, AlKα AlKβ,

The results are summarized in the following table:

<table>
<thead>
<tr>
<th>Compound</th>
<th>Pressure Coefficient (meV/kbar)</th>
</tr>
</thead>
<tbody>
<tr>
<td>InN</td>
<td>3.0 ± 0.1</td>
</tr>
<tr>
<td>In-rich In$_{1-x}$Ga$_x$N</td>
<td></td>
</tr>
<tr>
<td>In$<em>{0.5}$Al$</em>{0.5}$N (x = 0.25)</td>
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however, possess a large miscibility gap which has limited the achieved As content within the GaN1-yAsy system to only y ≤ 0.03. An As content of y ≥ 0.07 is considered necessary for 550 nm emission. We report the growth and properties of N-rich GaN1-yAsy alloy with As content over the range of y ≤ 0.064. GaNAs layers were grown to a thickness of 0.25 μm on GaN layers on sapphire substrates by low-pressure (1.0 Torr) metalorganic vapor phase epitaxy. The sources were trimethyl gallium, ammonia, and tertiarybutyl arsenic.

The carrier gas was hydrogen and the growth temperature was 700-750 ºC. The epilayer layers were characterized by X-ray diffraction (XRD) and atomic force microscopy (AFM). Electron probe microanalysis (EPMA) was used to determine As content in the film. The electronic structure was monitored by optical absorption and reflectivity measurements. The GaNAs layers possessed a yellow hue and had specular surfaces. AFM measurements determined a typical root mean square surface roughness of 0.7 nm for a 18-nm-thick GaN0.98As0.02 layer. Each sample had two diffraction peaks one from the underlying GaN and the other attributed to the GaNAs layer on the low-angle side of the GaN peak in its XRD rocking curve. No peaks that were related to As-rich GaNAs phases were observed in the wide range of XRD #2/3 spectra. The As incorporation into the GaNAs layers increased through both a decrease in the growth temperature as well as a decrease in V/III ratio from 13000 to 1400. These observed trends are similar to that found in other III-V alloy systems, such as GaAsSb. At high V/III ratios, thermodynamic constraints restrict the incorporated As to a low value. Low V/III ratios favor a kinetically limited competition and incorporation of the anion species. Through the use of growth conditions which enhance these kinetic processes, alloy compositions within the miscibility gap were achieved. The highest achieved value of As content of 64% was obtained by both decreasing the growth temperature and the V/III ratio. To our knowledge, this is the highest As content of N-rich GaNAs alloy that has been reported to date. The results of the optical measurements in regard to determining the optical band gap of the material will be discussed.

4:45 PM Y12.11
Abstract Withdrawn