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<td><strong>SUNDAY</strong></td>
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<td>PM</td>
<td>Session A: LED and Laser I</td>
<td>Session B: Microwave Devices I</td>
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<td>PM</td>
<td>Session G: Quantum Dots: Growth</td>
<td>Session H: Epitaxial Growth for Electronic Devices</td>
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<td>Session J: Deep UV LEDs and Lasers</td>
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<td>PM</td>
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<td>Session R: Optical Characterization of Lasers</td>
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<td>Session W: Nonpolar and Semipolar Materials and Devices II</td>
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<td>PM</td>
<td>Session Y: Optical and Structural Characterization and Related Topics</td>
<td>Session Z: Nonpolar and Semipolar Materials and Devices III</td>
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<td>Session HH: InN: Surface and Electronic Properties</td>
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<td>Session MM: Defects and Structural Characterization</td>
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<td>Session QQ: Special LED Closing Ceremony</td>
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*Registration 10:00-11:00 AM*
*Registration 7:00 AM-5:00 PM*
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# Session Listing

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<td>Session C: Bulk Growth and HVPE I</td>
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<td>Session L: Sensors and Characterization I</td>
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7th International Conference of Nitride Semiconductors
Technical Program

Opening Ceremony and Plenary
Monday AM  Room: 313/314/315/316  September 17, 2007  Location: MGM Grand Hotel Conference Center

9:00 AM Opening Ceremony
9:30 AM Plenary Speaker
10:30 AM Break

Session A: LED and Laser I
Monday AM  Room: 313/316  September 17, 2007  Location: MGM Grand Hotel Conference Center

11:00 AM Invited
A1, High-Power III-Nitride Based Light Emitting Diodes: Progress and Challenges: Werner Goetz; 1Philips Lumileds Lighting Company
After almost 20 years of intense research, III-nitride based light emitting diodes (LEDs) have now reached performance levels that rival and in many cases exceed the capabilities of existing light sources utilized for illumination or display backlighting. Especially high-power LEDs (P_i >0.5 W) have recently exhibited efficiencies that surpass high quality fluorescent lamps. For example, cool-white phosphor-conversion LEDs with luminous efficacy in the 100 lm/W regime (350 mA) have been reported. However, significant challenges still exist that today delay LEDs from being the light source of choice for general lighting applications. Paramount is production cost, but also issues such as the relatively low external quantum efficiency of green LEDs, the ubiquitous high drive current efficiency reduction, and the inability to precisely target the “white-point” of phosphor conversion LEDs with today’s production technology remain on the forefront of III-N LED focused research and development.

11:30 AM Invited
A2, Gross Well-Width Fluctuations in InGaN Quantum Wells: Rachel Oliver; Nicole van der Laak; Menno Kappers; Colin Humphreys; University of Cambridge
Gross fluctuations in quantum well (QW) width have been observed in commercially-available green light emitting diodes. Such fluctuations are found in green-emitting quantum wells which are subjected to an anneal or temperature ramp prior to capping. Atomic force microscopy and transmission electron microscopy (TEM) studies of eplayers and QWs reveal that these fluctuations arise from a network of interlinking InGaN strips, which are found (using TEM) to be indium-rich at their centres. Plan-view TEM indicates that ~90% of all threading dislocations (TDs) intersect the QW plane between the InGaN strips. Excitons may be localised at the strips’ centres, preventing non-radiative recombination at TDs. The orientation of strips in the network is found to be strongly anisotropic and this anisotropy correlates with the alignment of step-edges in the underlying GaN. It is hence suggested that the network structure forms via the decomposition of In-rich regions arising at or near step-edges.

12:00 PM
A3, Hexagonal Truncated Pyramidal LEDs through Wafer Bonding of ZnO to GaN and Laser Lift Off: Daniel Thompson; Akihiko Murai; Steve DenBaars; Umesh Mishra; Shuji Nakamura; University of California, Santa Barbara
We report on a hexagonal pyramid LED produced by direct wafer bonding of a MOVCVD grown GaN LED on sapphire to a n-type ZnO wafer, and laser lift off. Laser lift off was used to remove the sapphire of the GaN wafer, allowing creation of contacts to the n face of the GaN LED. Contacts to the ZnO allow for the creation of a vertical current path. Selective etching was used to form truncated hexagonal pyramids of the ZnO. We report on a comparison of the output power and efficiency to a GaN LED with truncated ZnO pyramid on sapphire. Both samples were packaged on silver headers with a silicone dome. We report that there is an increase of 11% output power under 20mA pulsed measurements between this laser lift off structure and a GaN LED and ZnO wafer bonded structure with no sapphire removal.

12:15 PM
A4, Optical Properties of Nitride Laser Structures Grown along a Non-Polar Crystallographic Direction: Henryk Teissseyre; I. Grzegory; C. Skierbiszewski; A. Khachapuridze; A. Feduniewicz-Zmuda; M. Siekacz; B. Luczmi; G. Kamler; M. Krysko; T. Suski; P. Perlin; S. Porowski; Polish Academy of Sciences, Institute of High Pressure Physics
Due to their undesirable spontaneous and piezoelectric properties, nitride structures grown along polar direction are subject to high built-in electric fields. A promising means of overcoming the effects related to built-in electric fields and, thereby, obtaining higher quantum efficiencies is to grow nitrides along a non-polar direction. It is our intention to report our recent progress on non-polar homo-epitaxial structures grown by PAMEB along the non-polar direction. As a substrate we used GaN bulk crystals grown by the High Pressure Solution method and overgrown by HVPE. As has been previously reported, non-polar AlGaN/GaN quantum wells possess sharp excitonic lines. We present optically pumped laser action on separate confinement heterostructures. Laser action is clearly proved by spontaneous emission saturation, abrupt line narrowing, and the strong TE polarization of output light. We also performed a comparison between the optical properties of polar and non-polar laser structures.

Session B: Microwave Devices I
Monday AM  Room: 314/315  September 17, 2007  Location: MGM Grand Hotel Conference Center

11:00 AM Invited
B1, GaN-on-Silicon RF Power Devices–Current State and Future Directions: Kevin Linthicum; 1Nirtronex Corporation
A GaN-on-silicon platform technology has been developed to provide the performance advantages of GaN combined with the manufacturing advantages of silicon. The NRF1 process technology is currently undergoing 28V operation and released for production. Extensive reliability studies have been performed yielding demonstrated E_A=2.0eV predicting an MTTF of 10E7 hours at 200°C junction temperatures. Air cavity and plastic overmold assembly techniques are used for product offerings available today. The NRF1 process technology is currently undergoing 48V qualification and will support the production release of a family of high power transistors for WiMAX, Cellular and Broadband market applications.

11:30 AM B2, Invited
High Efficiency GaN HEMT Amplifiers: Bill Pribble; 1Cree-GaN
Abstract not available.

12:00 PM
B3, High-Efficiency GaN HEMTs on 3-Inch Semi-Insulating SiC Substrates: Patrick Waltewei; Wolfgang Bronner; Rüdiger Quay; Michael Dammann; Stefan Müller; Rudolf Kiefer; Brian Raynor; Michael Mikulla; Günther Weimann; Fraunhofer Institute for Applied Solid State Physics
AlGaN/GaN HEMT structures are grown on semi-insulating SiC substrates by metal-organic-chemical-vapour-deposition with sheet resistance non-uniformities better than 2%. Device fabrication is performed using standard processing techniques involving both e-beam and stepper lithography. HEMTs demonstrate excellent high-voltage stability and large efficiencies. Devices with 0.5μm gate length exhibit two-terminal gate-drain breakdown voltages in excess of 160V across the entire 3-inch wafer with...
parasitic gate/drain currents in the low μA/mm range when biased at 120V drain bias under pinch-off conditions. Load-Pull measurements (800μm gate periphery; 2GHz) return both a linear relationship between bias-voltage and output-power as well as power-added-efficiencies >55% up to VDS=72V for which an output-power-density of 9W/mm with 25dB linear gain is obtained. Initial reliability tests indicate a promising device stability above 1000h. Less than 20% drain current degradation under different DC-stress conditions (U_DS=50V, P=2.5W/mm, T_CHANNEL=90°C and U_DS=10V, P=7W/mm, T_CHANNEL=275°C) as well as less than 0.2dB gain reduction under RF-stress (2GHz, U_DS=50V, P=5.5W/mm, 3dB compression, T_CHANNEL=160°C) are obtained.

12:15 PM
B4, Power Performance of AlGaN/GaN HEMTs Grown on SiC by Ammonia MBE: Christiane Poblenz; Andrea Corrion; Felix Recht; Chang Soo Suh; Rongming Chu; Likun Shen; James Speck; Umesh Mishra; *University of California, Santa Barbara

We report on AlGaN/GaN high electron mobility transistor (HEMT) structures grown by ammonia MBE on semi-insulating 4H-SiC(0001) substrates with excellent power and efficiency performance. A standard HEMT with a 30 nm UID Al0.30Ga0.70N cap and a dislocation density of ~1010 cm-2 exhibited a Hall mobility of 1643 cm2/Vs and a sheet charge density of 1.0 x 1012 cm-2. A maximum drain current density of 1.05 A/mm, Id, of 24 GHz and fmax of 54 GHz were measured for 0.7 μm gate length devices. At 4 GHz, an output power density of >10 W/mm with an associated PAE of 63% at VDS = 48 V was achieved. Gate leakage was reduced in these structures through use of a fluoro plasma surface treatment. These results are the highest reported for ammonia MBE on SiC at 4 GHz and demonstrate the potential of ammonia MBE to produce high quality AlGaN/GaN HEMT devices.

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Session C: Bulk Growth and HVPE

Monday AM
September 17, 2007
Location: MGM Grand Hotel Conference Center

11:00 AM Invited
C1, Preparation of 3-Inch Free-standing GaN Substrates by Hydride Vapor Phase Epitaxy with Void-avoided Separation: Yuichi Oshima; Takehiro Yoshida; Takeishi Eri; Kazutoshi Watababe; Masatomo Shibata; Tomoyoshi Mishima; *Hitachi-cable, Ltd.

Manufacture of 3-inch GaN substrates was attempted. Hydride vapor phase epitaxy and void-avoided separation (VAS [1]) were utilized for fabrication of freestanding GaN substrates. This study used 3.4-inch-diameter (0001) sapphire as base substrate. HVPE growth was performed on a 3.2-inch-diameter area of the base substrate. After HVPE growth, the thick GaN layer was spontaneously separated from the base substrate due to thermal stress. As a result, a GaN substrate with a diameter of approximately 3.2 inches was obtained. No cracks were generated during repetition of the same process several times. There was no additional difficulty in the separation process compared to 2-inch substrates. Therefore, further enlargement of the diameter is likely possible using the VAS method. This result greatly contributes to the potential for high-performance, low-cost nitride devices. [1] Y. Oshima et al.: Jpn. J. Appl. Phys. 42 (2003) L1.

11:30 AM
C2, Lateral Epitaxial Overgrowth of AlN by Hydride Vapor Phase Epitaxy: Derrick Kamber; Scott Newman; Yuan Wu; Steven DenBaars; James Speck; Shuji Nakamura; *University of California, Santa Barbara

The threading dislocation densities of AlN films were substantially reduced via lateral epitaxial overgrowth (LEO) by hydride vapor phase epitaxy (HVPE). The AlN films were grown on patterned 6H-SiC substrates containing elevated mesas separated by trench regions. A variety of different stripe patterns were used to produce fully coalesced AlN films. Transmission electron microscopy (TEM) was used to assess the structural quality of these films. TEM analysis determined that the dislocation density in the laterally grown wing regions was less than 8.3×109 cm-2 as compared to 1.8×1010 cm-2 in the seed regions. Atomic force microscopy revealed that the films have a smooth surface morphology with a rms roughness of 0.71 nm over 10×10 μm2 sampling areas. These results represent the first reported AlN LEO by HVPE. Moreover, we have achieved the lowest dislocation density for HVPE growth of AlN, and the results are comparable to the best MOCVD growth results.

11:45 AM
C3, Growth of the Full-Scale GaN Single Crystal Substrate Using Na Flux Method: Fumio Kawamura; Yoshihiro Kitano; Masaki Tanpo; Naoya Miyoshi; Mamora Imade; Masashi Yoshimura; Yasuo Kitaoka; Takatomo Sasaki; Yusuke Mori; *Osaka University

We succeeded in growing a GaN single crystal substrate with diameter of about two inches using the Na flux method. Our success is due to the development of a new apparatus for growing large GaN single crystals. The crystal grown in this study has a low dislocation density of 2.3×107 (cm-2). The secondary ion mass spectrometry (SIMS) technique demonstrates that the Na element is difficult to be taken in the crystal in both the + and – c directions, resulting in a Na concentration of an order of 1014 (cm-3) in the crystal. Our success in growing a two-inch GaN substrate with a low impurity content and low dislocation density should pave the way for the Na flux method to become a practical application.

12:00 PM
C4, Free-Standing Zinc-Blende (Cubic) GaN Substrates Grown by Modified Molecular Beam Epitaxy Process: C. Thomas Foxon; Sergey Novikov; Nicola Stanton; Richard Campion; Anthony Kent; *University of Nottingham

We demonstrate bulk, free-standing, zinc-blende (cubic) GaN substrates grown by a modified molecular beam epitaxy process. We have grown free-standing cubic GaN layers up to 60 microns in thickness. Even though our growth rate is currently not particularly fast, it is already comparable with the growth rate for bulk wurtzite GaN crystals from the liquid Ga at high pressure. We present measurements, which confirm the cubic nature of the GaN wafers and show that the hexagonal content of the material is less than 10%. Cubic (001) GaN does not exhibit the spontaneous and piezoelectric polarization effects associated with (0001) c-axis wurtzite GaN, therefore, our free standing GaN wafers make ideal lattice-matched substrates for the growth of cubic GaN-based structures for blue and ultraviolet optoelectronic devices, and high power and high frequency electronic applications.

12:15 PM
C5, Growth of Thin Protective AlN Layers on Sapphire Substrates at 1065°C for Hydride Vapor Phase Epitaxy of AlN above 1300°C: Junpei Tajima; Yuki Kubota; Rie Togashi; Hisashi Murakami; Yoshinao Kumagai; Akinori Koukitu; *Tokyo University of Agriculture and Technology

Hydride vapor phase epitaxy (HVPE) of a thick AlN layer on a foreign substrate is one of a promising method for preparation of a freestanding AlN substrate. Recently, our group has succeeded in HVPE of AlN layers on sapphire substrate above 1200°C with an aid of a resistance heating susceptor. However, the crystalline quality of the AlN layers was not necessarily good due to surface decomposition of sapphire substrate at this temperature. In this paper, effects of thin protective AlN layer growth on sapphire above 1200°C are reported that FWHM values of X-ray diffraction rocking curves for symmetric (0002) and asymmetric (10-10) AlN, as well as surface morphology, are greatly improved by the protective layer growth. Concentration of oxygen impurity in the grown layer was also reduced owing to the protection of sapphire substrate.
Technical Program

Session D: LED and Laser II

Monday PM
September 17, 2007
Room: 313/316
Location: MGM Grand Hotel Conference Center

2:00 PM Invited
D1, ThinGaN Power-LED Demonstrates 100 lm at 527 nm: Matthias Peter; P. Stauss; A. Walter; J. Bauer; B. Hahn; ‘OSRAM Opto Semiconductors GmbH; ‘OSRAM Opto-Semiconductors GmbH

Recent progress in the epitaxy of green InGaN LEDs in combination with an improved 1 mm² chip design leads to a significant improvement of output power for green LEDs: 99.1 lm at 350 mA were demonstrated for a 1 mm² ThinGaN Chip at 527 nm, mounted in a Dragon package with spherical lens. Efficacies of 113 lm/W at 100 mA and 73 lm/W at 350 mA have been achieved.

2:30 PM Invited
D2, Blue Lasing at Room-Temperature in a Lattice-Matched AlInN/GaN Vertical Cavity Surface Emitting Laser: Eric Feltin; Gabriel Christmann; Julien Dorsaz; Antonino Castiglia; Anas Mouit; Pierre Stadelmann; Jean-François Carlin; Raphael Butté; Nicolas Grandjean; Stavros Christopoulos; Giorgio Baldassarri; Alastair Grundy; Pavlos Lagoudakis; Jeremy Baumberg; ‘EPFL; ‘University of Southampton

III-nitride optoelectronic devices have recently undergone a tremendous development with the commercialisation of white light emitting diodes and UV edge-emitting lasers. However, electrically driven compact laser source such as vertical cavity surface emitting lasers (VCSELs) have not been demonstrated so far. We now report on the lasing action at 422nm under optical pumping of a crack-free hybrid microcavity with a bottom lattice-matched AlInN/GaN Bragg mirror and a top SiOx/SiNx Bragg mirror. The maximum peak reflectivity of both mirrors exceeds 99% and the quality factor of the microcavity reaches 2800. The cavity is formed by n and p-type regions, an AlGaN electron blocking layer and only three InGaN/GaN quantum wells. Such a design is identical to that of an electrically driven VCSEL. The high finesse of the microcavity leads to lasing at room temperature for a power density of only 200μJ/cm², the lowest threshold reported so far for a nitride VCSEL.

3:00 PM
D3, Low Noise Characteristics of AlGaN/GaN-Based Self-Pulsating Laser Diodes: Toshiyuki Ohata; Nobuyoshi Kitaigama; Makoto Ohata; Hiroyauchi Ichinokura; Masaru Kuramoto; ‘Sony Shiroishi Semiconductor Inc

We have successfully produced practical self-pulsating AlGaN-based laser diodes (SP-LDs) that have low noise characteristics even with an optical feedback of 1% at a high temperature of 75°C. Our fabricated SP-LD is using a saturable absorber layer (SAL). We intentionally introduced reactive ion etching (RIE) damage to the SAL in order to reduce the carrier lifetime in the SAL by controlling the distance between the SAL and the dry-etched surface. The threshold currents of a fabricated SP-LD at 25 and 75°C were 38.8 and 54.4 mA, respectively. We also demonstrated that it is possible to suppress the relative intensity noise (RIN) even under the conditions of high temperature (75°C) and an optical feedback of 1% (RIN ≈ 125 dB/Hz). These results indicate that practical SP-LDs for use in optical storage devices can be produced by inducing dry etching damage in the SAL.

3:15 PM
D4, Beam Quality of Blue InGaN Laser for Projection: Uwe Strauss; Christian Rambolz; Christoph Eichler; Alfred Leil; Stephan Lutgen; Soenke Tautz; ‘Marc Schillgalies; Stefanie Brueninghoff; ‘OSRAM Opto Semiconductor

The light source of choice for laser projection will be a long wavelength nitride laser because of its high wall plug efficiency and because of the small size compared to blue light by second harmonic generation. High quality of the far field is required for laser projection. However, optical confinement by GaN/AlGaN structures becomes increasingly difficult if wavelengths shift from 405 nm to the true blue spectrum. We will show excellent far fields by suppression of higher laser modes and by improved waveguiding, respectively. We present simulations of laser modes as a function of ridge widths. The slow axis far field is improved by absorber layers to guarantee M<1.5. Sufficient vertical confinement of the laser light by thick cladding layers is necessary to suppress laser modes guided inside the substrate. We present 440 nm lasers for projection with threshold densities as low as 2kA/cm² and slope efficiencies of 1W/A.

2:00 PM Invited
E1, GaN MMICs for RF Power Applications in the 50 GHz to 110 GHz Frequency Range: Miro Mirovic; Ara Kourdoglian; Ivan Milosavljevic; Paul Hashimoto; M. Hu; M. Antcliffe; P. Willadsen; W. Wong; Adele Schmitz; R. Bowen; David Chou; ‘HRL Laboratories LLC

Solid state RF power sources for frequencies exceeding 50 GHz are currently realized almost exclusively in GaAs and InP material systems. Until recently GaN-based devices were not seriously considered for power applications at frequencies that are higher than 50 GHz, due to difficulty with material processing. In 2006 we reported at IEDM outstanding potential of GaN MMIC technology for RF power applications at frequencies exceeding 80 GHz. The first reported W-band GaN power MMIC had over 16 dB of saturated power gain in a frequency range between 78 GHz and 88 GHz and produced almost the same output power at this frequency band as the state of the art InP HEMT MMICs with 10 times larger output device periphery. In this presentation we will report the latest advances in our W-band GaN MMIC technology and discuss the impact of GaN technology on the development of high frequency millimeter-wave power modules.

2:30 PM
E2, Deep Submicron AlGaN/GaN HEMT with Ion Implanted Source/Drain Regions and Nonalloyed Ohmic Contacts: Yi Pei; ‘University of California, Santa Barbara

We have demonstrated the first deep submicron AlGaN/GaN HEMTs with nonalloyed ohmic contacts by ion implantation, which show an excellent high frequency performance that is comparable to state of the art AlGaN/ GaN HEMTs with alloyed contacts. Nonalloyed ohmic contacts with 0.2 μm were achieved by Si implantation into source/drain regions with a dose of 5x15 cm², energy of 50 kev and +40° incident angle, followed by 1280°C MOCVD annealing. For a Lg=150 nm, Wg=2μm HEMT, a peak gm of 490 ms/mm was achieved. FT was 91 GHz and fMAX was 167 GHz at a VDS of 16 V. These results show implantation very promising for improving device high frequency performance.

2:45 PM
E3, Ultra-Short Channel AlGaN/GaN FETs for Future High-Speed and High-Transconductance Applications: David Deen; Tom Zimmermann; Yu Cao; Debdeep Jena; Huilin (Grace) Xing; ‘University of Notre Dame

While the AlGaN/GaN HEMTs have been scaled down for higher speed (>200 GHz), it is clear that a thin AlN could serve well as gate barrier due to its large bandgap (6.2 eV) and high permittivity (~ 8.5). AlN/GaN based HEMTs have been demonstrated by several groups to date, however, they all seemed to be limited by the relatively poor AlN, manifested by the channel 2DEG low mobility (< 400 cm²/Vs). Recently in our lab, high quality AlN up to 5 nm have been grown on GaN without cracks, exhibiting 2DEG...
density as high as 4e13 cm-2 and mobility as high as 1200 cm2/Vs. HEMTs have been fabricated on these heterostructures with various AlN barrier thicknesses: 2.3, 3.5 and 5 nm. E.g. the 5 nm AlN/GaN HEMT (Lg=3 μm) showed an output current of 800 mA/mm and a transconductance of about 180 mS/mm. Our detailed findings will be then presented.

3:00 PM  
E4, Deeply Recessed AlGaN/GaN HEMTs with Deep Submicron Gates:  
Rongming Chi; Yi Pei; Likun Shen; Christiane Poblenz; James Speck; Umesh Mishra;  
‘University of California, Santa Barbara  
For applications at K-band and beyond, it is attractive to develop dispersion free AlGaN/GaN HEMTs without using the field-plate. By having the device surface far from the 2DEG, and thereby minimizing the dispersion, we have developed deeply recessed AlGaN/GaN HEMTs with exceptional performance at C- and X-band. In this report, we present our recent work on scaling the gate length of the deeply recessed HEMTs. The fabricated device has a saturation current of 0.75 A/mm, and a gate-drain breakdown of 180 mS/mm.  

3:30 PM  
E5, Laterally Engineered Field-Plate GaN HEMTs for mmWave Applications:  
Karim Boutros; Keisuke Shinohara; Andres Paniagua; Berinder Brar;  
‘Teledyne Scientific  
A laterally Engineered Field Plate (EFP) design is implemented to obtain a field-plate, 30nm gate structure with a minimum added capacitance due to the presence of the field plate. By reducing the field plate length, and simultaneously placing it away from the gate, we are able to reduce the field plate capacitance while maintaining its effectiveness in reducing the peak electric field at the gate edge. GaN HEMT EFP devices were fabricated with 30nm gate lengths, and 70nm field plates. A three-terminal breakdown voltage (VBD) of 63V was measured for the 30nm EFP device. This VBD represents a 2x improvement over the breakdown of 100nm T-gate devices fabricated on the same wafer. The device had an extrinsic ft of 65GHz and an FMAX of 95GHz. These results are very encouraging because they show that the deep submicron deep recess technology is very promising for achieving high power performance at higher frequencies.

3:15 PM  
F1, Chemical Lift-Off of GaN Epitaxial Films Grown on c-Plane Sapphire:  
Yoshinao Kumagai; Toru Nagashima; Hisashi Murakami; Kazuya Takada; Akinori Koukitu;  
‘Tokyo University of Agriculture and Technology; ‘Tokuyama Corporation  
We developed a Vertical Hydride Vapor Phase Epitaxy tool for the growth of up to 7 cm long GaN boules of 2 inch size. prototypes were built and optimized with respect to total growth rate, parasitic ammonium chloride deposition and growth uniformity of the boule. A shear flow between the reactive species GaCl and NH3 provides separation and, thus, avoids pre-reactions. Special attention was paid to the avoidance of cold spots along the way from the growth zone into the particle trap outside of the reactor chamber. In AFM measurements a 250 nm thin layer features parallel steps of 10-15 nm height spaced at 5 nm. For a 2 mm thick layer the surface becomes irregular with pits of about the same depth. The RMS roughness was measured to be 3 nm for a 10x10 μm² scan field in both cases. Additional results on EPD and photoluminescence will be presented.

3:00 PM  
F4, Characterization of Low Defect Density Non-Polar Native GaN Substrates:  
K.-Y. Lai; V. D. Wheeler; J. A. Grench; M. A. L. Johnson; A. D. Hansen; Keith Evans;  
‘North Carolina State University; ‘Kyma Technologies, Inc.  
Non-polar GaN’s predicted potential to improve the efficiency of LEDs was recently corroborated by researchers using a low-defect-density non-polar “native” GaN substrate. Prior attempts by others to fabricate efficient non-polar GaN LEDs appear to be stacking-fault defect-limited due to prior use of non-polar “template” GaN substrates. We report on the structural characterization, using cathodoluminescence spectroscopy and secondary electron microscopy, of low-defect-density non-polar native GaN substrates which were produced by transverse wafering of low-defect density c-plane GaN boules grown by hydride vapor phase epitaxy (HVPE). Very low non-radiative recombination center densities of 10^11 cm^-2 and lower were observed, consistent with very low concentrations of extended defects. Results of GaN HVPE regrowth experiments will also be presented showing appreciable anisotropy in growth rate and consistent with no appreciable extended defect generation in the epilayers.

3:45 PM  
F5, Self-Separation Mechanism of AlN Thick Layers Grown on SIC:  
G. Reza Yazdi; Finn Giuliani; Mikael Svayjarvi; Lars Hultman; Rositza Yakimova;  
‘Linkoping University  
This paper presents a new way to fabricate freestanding AlN wafers by physical vapor transport technique. We will report the morphological evolution from discontinuous growth, resulting in arrays of AlN microrods,
Technical Program

3:15 PM  
F6, Homo Epitaxial Seeding and Grain Evolution of AlN Bulk Crystals:  
Carsten Hartmann; Juergen Wollweber; Christoph Seitz; Martin Albrecht;  
Roberto Fornari; 1 Institute for Crystal Growth  

PVT growth, the most accepted technique to grow AlN single crystals,  
is performed. A precondition for sizeable and low defect crystals is homo-  
etaxial seeding. The grain evolution described in this paper is considered  
as an effective method to develop monocrystalline seeds by using an iterative  
procedure. Supported by temperature field calculations a special crucial  
design and substrate holder geometry is developed. First AlN boules, 35 mm  
in diameter and 15 mm long, were grown in an inductively heated reactor  
on TaC crucible lids. The largest grains (4-5 mm diameter) were separated,  
cut in wafers, polished and used for the subsequent growth runs. Successful  
and reproducible epitaxial seeding is demonstrated and proved by EBSD  
measurements. A pre-treatment process, a deoxidizing ambiance and an  
adapted temperature-gradient-control inhibit impurity deposition on the  
seed. Longitudinal cuts show the grain evolution with coarsening angels of  
10 – 15°. The crystals are 8-10 mm in diameter.

3:30 PM  Break

Session G:  
Quantum Dots: Growth

September 17, 2007  
Room: 313/316

4:00 PM Invited  
G1, [0001]; [11-20] and [1-100] GaN Quantum Dots: Growth and Optical  
Properties: Bruno Daudin; 1 CEA/Grenoble  

Quantum dots (QDs) are of particular interest in highly defective  
nitride materials and are possible candidates to form active layers of a new  
generation of light emitting diodes. In particular, growth of nonpolar QDs is  
especially attractive to face the issue of internal electric field present in  
[0001] heterostructures, detrimental to radiative recombination efficiency.  
Along these lines molecular beam epitaxy growth of non polar [11-20] and  
[1-100] GaN QDs using [11-20] and [1-100] SiC substrates will be described.  
Their structural properties will be discussed. In particular, it will be shown  
that a wide variety of morphological shapes, ranging from quantum wells to  
QDs and quantum wires, can be obtained depending on growth conditions.  
The optical properties of non polar [11-20] and [1-100] single dots will be  
presented and compared to that of their polar [0001] counterparts. As  
expected, it is found that luminescence decay time is shorter (around 200 ps)  
in non polar QDs than in polar ones (in the 10 ns – 100 ms range), due to  
electric field reduction.

4:30 PM  
G2, Investigations of InN Quantum Dot Growth by Metal Organic  
Vapor Phase Epitaxy: Bernard Gil; Olivier Briot; Mathieu Morret; Sandra  
Ruffenach; 1 CNRS  

We investigate the growth of InN quantum dots by MOVPE on different  
foreign substrates and using different gas vectors.

4:45 PM  
G3, Mechanisms of Quantum Dot Formation in InGaN Layers Grown by  
MOVPE: André Strittmatter; Til Bartel; Lars Reifmann; Robert Seguin;  
Axel Hoffmann; Dieter Bimberg; 1 Technische Universität Berlin; 2 Otto-  
von-Guericke Universität Magdeburg  

Quantum dot formation in InGaN layers grown by MOVPE on Si(111)  
substrates was investigated by transmission electron microscopy as well as  
by cathodoluminescence. Two sets of samples grown either with varying In  
content (10%-25%) or with varying thickness (0.5 - 4 nm) of the InGaN  
layers were studied. Thereby, the impact of both parameters on the QD  
formation can be distinguished. In fact, QDs are evidenced in all layers  
either via locally via XTEM images or by narrow lines (FWHM<1 meV) in the  
cathodoluminescence spectra recorded from sub-micron size apertures  
formed in metal masks. All InGaN layers are characterized by local In  
clustering. The In distribution functions determined from the HRTEM cross  
sections show identical halfwidths independent of growth parameters.

5:00 PM  
G4, Optical Properties of Single and Multi-Layer InGaN Quantum Dots:  
Kathrin Sebald; Joachim Kalden; Henning Lohmeyer; Sandra Herlufsen;  
Jürgen Gutowski; Tomohiro Yamaguchi; Christian Tessarek; Detlef  
Hommel; 1 University of Bremen, Semiconductor Optics, Institute of Solid  
State Physics; 2 University of Bremen, Semiconductor Epitaxy, Institute of  
Solid State Physics  

In the last years much effort was spent in the realization for InGaN  
quantum dots (QDs) in order to achieve efficient devices emitting in the  
UV-blue spectral region. In this contribution we will present the optical  
properties of single InGaN QDs grown by MOVPE. The samples were  
structured into mesas by focused-ion-beam etching and investigated by  
micro-photoluminescence measurements. The QDs are characterized by a  
high temperature stability of their emission up to 150 K as well as spectral  
diffusion effects occurring only at high excitation densities. Furthermore, the  
polarization of individual QD emission lines was analyzed giving an insight  
into their geometrical shape. Additionally, the optical properties of mesa  
structured InGaN QD stacks were investigated up to room temperature in  
order to get information on the influence of the stacking on the properties  
of the QDs as well as indications for coupling effects between the QDs.

5:15 PM  
G5, Spectral Linewidth Control of Hexagonal Gallium Nitride Quantum  
Dots: Takeshi Kawano; Satoshi Kako; Christian Kindel; Yasuhiko  
Arakawa; 1 Institute of Industrial Science; 2 Collaborative Institute for Nano  
Quantum Information Electronics; 3 Research Center for Advanced Science  
and Technology; 4 University of Tokyo  

Epitaxially grown GaN QDs embedded in AlN have attracted much  
attention for single-photon source (SPS) operating at room temperatures  
because of strong confinement effect, large optical photon energies, and  
large biexciton binding energy. So far, we have demonstrated triggered  
single-photon generation from a single GaN QD at temperatures up to  
200K. One of the obstacles to realize SPS operating at room temperatures  
is spectral-diffusion processes which cause the linewidth broadening due to  
the defects in the vicinity of GaN QDs. By means of annealing at temperatures  
of 1180°C for 10min and improving AlN buffer layer by inserting alternative  
providing growth where the material sources of Al and N are provided  
alternatively, an average of spectral linewidth of GaN QDs became reduced  
from 13.5 meV to 8.8 meV and from 13.3 meV to 11.1 meV, respectively.  
We believe that spectral linewidth will become much reduced by combining  
these two methods.
H1, High Quality N–Rich GaN Growth by Plasma–Assisted Molecular Beam Epitaxy for Electronic Devices: Gregor Kohlmueller; Rong Ming Chiu; Feng Wu; Christiane Poblenz; Andrea Corrion; Umesh Mishra; James Speck;1,1 University of California, Santa Barbara

Exploitation of N–rich growth conditions at temperatures of thermal decomposition was demonstrated to yield a layer–by–layer growth mode during the PAMBE growth of (0001) GaN. Consequently, smooth surface morphologies were achieved for thick GaN films with rms roughness < 1 nm and no new dislocations generated. The capacity of these novel growth conditions were also reflected by record RT electron mobilities greater than 980 cm2/Vs at carrier densities in the 1E16 cm-3 region, surpassing the commonly insulating nature of GaN grown under N–rich conditions at lower temperatures due to reduced impurity incorporation. Utilizing the N–rich/high–T conditions for the growth of AlxGa1–xN HEMTs on 4H–SiC, we observed a clear trend for dislocation reduction while maintaining smooth surfaces. Non–optimized transistor structures exhibited very low buffer leakage, 2DEG mobilities and drain currents in excess of 1510 cm2/Vs and 1.2 A/mm respectively, comparing very well with state–of–the–art grown devices by MOCVD and MBE.

H2, Optimization of Regrowth Interface in III–Nitride-Based Heterostructure Field Effect Transistors Grown by MOCVD: Jianping Liu; Jae–Hyun Ryoo; Wonseok Lee; Yun Zhang; Shyh–Chiang Shen; Russell Dupertuis;1 Georgia Institute of Technology

For III–nitride based HFETs, the semi–insulating property of the layer including the buffer layer and the substrate underneath the channel is required in order to achieve a sharp current pinch–off and high–frequency device operation. For the case of the growth on GaN template and Si substrates, the growth interface between the epitaxial layer and the substrate template is a critical region of the device. In order to remove the interface charged layer that is inevitably introduced during the substrate preparation and/or epitaxial growth, we studied three effects on charged layer on GaN templates and free–standing substrates: (1) Fe doping near the interface, (2) chemical cleaning, and (3) PEC (photoelectrochemical) etching. We will report in detail on the interface charge behavior depending on Fe doping scheme and surface treatment and propose the mechanism of interface charge removal. Also, performance characteristics of HFETs with and without interface charge will be analyzed.

H3, Ammonia Molecular Beam Epitaxy of AlGaN/GaN High Electron Mobility Transistors on 6H-SiC: Andrea Corrion; Christiane Poblenz; Feng Wu; Likun Shen; Felix Recht; Rongming Chiu; Chang Soo Suh; Umesh Mishra; James Speck; Materials Department, University of California, Santa Barbara;1 Electrical and Computer Engineering Department, University of California, Santa Barbara

The growth conditions for ammonia MBE of AlGaN/GaN HEMTs on 6H–SiC were optimized for surface morphology and dislocation density, and excellent RF performance was demonstrated. It was found that decreasing growth rates and increasing V/III ratios resulted in decreasing surface roughness. The TD density decreased with decreasing V/III ratio, which resulted in enhanced surface roughness and a transition from a two- to a three-dimensional growth mode. A two–step buffer was developed in which the first step was grown under low V/III ratio conditions to achieve low dislocation density, resulting in 25% reduction in dislocation density. A three micron sample with the two–step buffer had a dislocation density of 3 x 106 cm2; among the lowest values ever reported for MBE GaN growth on SiC.

Ammonia MBE AlGaN/GaN HEMTs were fabricated, and an output power of >10 W/mm with a PAE of 63% was achieved at 4 GHz.

H4, AlGaN/GaN HEMTs Grown by Molecular Beam Epitaxy on 3C-SiC/ Si(111): Yvon Cordier;1 Marc Portal;2 Sébastien Chenot;2 Olivier Toottereau;2 Marcin Zielinski;2 Thierry Chassagne;2 CRHEA-CNRS;2 NOVASIC Cubic SiC/Si(111) substrate is an interesting alternative for growing GaN. As compared with silicon, this substrate allows reducing the stress in GaN films due to both lower lattice and thermal expansion coefficient mismatch, and can provide better heat dissipation. In this work, we developed the epitaxial growth of 3C–SiC films on Si(111) by hot wall CVD. AlGaN/ GaN HEMT heterostructures were subsequently grown by MBE. Surface roughness and dislocation density (≤5E9 cm2) are at least at the same level as the ones of layers grown on bulk substrates while X–ray diffraction shows a single in–plane orientation for both GaN and 3C–SiC with respect to Si(111). Transistors and Hall effect devices were realized. GaN buffer layers are highly resistive and a 2D electron gas with a carrier density of 7E12 cm-2 and mobility of 1500 cm2/Vs has been obtained for a structure with an Al content x=25% in the AlGaN barrier.

H5, Fe–Doped GaN below and above the Solubility Limit: Growth and Characterization: Martin Quast;1 Michal Kiecana; Clemens Simbrunner; Tian Li; Andrea Navarro–Quedada; Matthias Wegscheider; Maciej Sawicki; Tomasz Dietl;1 Alberta Bonanni;1 Johannes Kepler Universität Linz;1 Polish Academy of Sciences

In order to shed light on the origin of high temperature ferromagnetism observed in magnetically doped semiconductors and oxides, we have undertaken comprehensive studies of MOVPE grown (Ga,Fe)N, which combine a detailed space–resolved chemical analysis by transmission electron microscopy and energy dispersive X–ray spectroscopy with a thorough magnetic, optical and electric characterization. Our investigations reveal the presence of coherent nanocrystals, presumably FeN, with the composition and lattice parameter imposed by the GaN host. Their presence and their non–uniform distribution over the film volume affect in a decisive way the magnetic and optical properties of the films. We find, in particular, ferromagnetic signatures such as spontaneous magnetization, which persist well above room temperature and whose magnitude increase with the Fe concentration above the solubility limit. We explain these observations in terms of a high critical temperature associated with magnetic- and shape anisotropy of the Fe3N nanocrystals.

H6, Inhibition of Regrowth Interface Contamination with New Fe Doped Templates for AlGaN/GaN HEMT Applications: Yvon Cordier;2 Nicolas Baron;1 Mohamed Azize; Sebastien Chenot; Olivier Toottereau; Jean Massies; CRHEA-CNRS; Picogiga International

Semi–insulating behaviour of GaN templates is required for high–frequency devices such as AlGaN/GaN high electron mobility transistors (HEMTs). To obtain such SI templates, two ways have proven to be efficient: the self–compensation by a huge amount of defects as dislocations and Fe modulation doping for a better crystalline quality (dislocation density < 1E9 cm-2). In this work, we show that by carefully designing the Fe doping profile into SI–GaN templates grown by MOVPE and by optimizing the MBE regrowth conditions, highly–resistive GaN buffer can be achieved on these epi–ready GaN-on– Sapphire templates without any addition of acceptors during the regrowth. As a result, high–quality high electron mobility transistors can be realized. Furthermore, we report on the excellent properties of two–dimensional electron gas and device performances with electron mobility superior to 2000 cm2/Vs at room temperature and off-state leakage current as low as 5 μA/mm at 100V.
Technical Program

Session I: Optical Characterization of Bulk Materials and Microcavities

Monday PM Room: 312/317
September 17, 2007 Location: MGM Grand Hotel Conference Center

4:00 PM Invited

11. High-Quality Nonpolar m-Plane GaN Substrate Grown by HVPE: Kenji Fujito; Kazumasa Kiyomi; Tae Mochizuki; Hirota Oota; Hideo Namita; Satoru Nagao; Isao Fujimura; Mitsubishi Chemical Corporation; 2Mitsubishi Chemical Group Science and Technology Research Center, Inc.

We have obtained relatively large size (about 10mm X 10mm) m-plane GaN substrates grown by HVPE. Typical values for the full widths at half maximum (FWHM) of x-ray rocking curves measured for the (10-10) and (10-12) reflections were 2535arcsec and 3040arcsec, respectively. The dislocation distribution was observed from the [10-10] direction by cathodoluminescence method. The dark spots density was less than 2.5X105cm-2. The surface roughness after the lapping and polishing was measured by atomic force microscopy and the RMS was less than 0.1nm. More detailed characteristics of our substrates will be presented in the conference. High-quality large size m-plane GaN substrate will enable to realize commercial production of nonpolar devices.

4:30 PM

12. Dephasing Studies of Exciton Fine Structure in Uniaxially-Strained GaN: Tetsuro Ishiguro; Yasunori Toda; Satoru Adachi; Katsuyuki Hoshino; Yasuhiko Arakawa; Hokkaido University; Yamaguchi University; University of Tokyo

Dephasing dynamics of exciton fine structure (EFS) in a GaN film on a-plane sapphire was observed and studied by utilizing a spectrally-resolved four-wave-mixing (SR-FWM) spectroscopy. In the sample, degenerate exciton states are split into their fine structures due to the exchange interaction induced by the anisotropic strain field of the substrate. Since the each exciton of FS is also highly polarized, the polarization dependent SRFWM spectra successfully resolve the dephasing dynamics in the individual resonances. The result shows a significant difference in the dephasing time between the A-exciton EFS (XAa and XAY), suggesting that exchange interaction is effective in the dephasing of excitonic polarization in GaN.

4:45 PM

13. Radiative Decay Times of Free and Bound Excitons in Bulk GaN: Bo Monemar; Plamen Paskov; Peder Bergman; Alexey Toropov; Tatiana Shubina; Akira Uedono; Linköping University; Uppsala University UNeil

Transient photoluminescence (TRPL) for high quality HVPE bulk GaN crystals are reported for temperatures 2 K to 300 K. The decay of the free exciton non-phonon (NP) line is short at 2 K, about 100 ps. The FE LO phonon replicas have a longer decay time, about 1400 ps at 2 K. The donor bound exciton (DBE) NP lines have an initial short (non-exponential) decay of 300 ps at 2 K, while the LO replicas have a decay about 1300 ps. The DBE two-electron transitions (TETs) exhibit a decay above 1 ns. We suggest a nonradiative surface recombination is important for the NP FE line, but not for the FE replicas, due to reabsorption. The DBE NP line decay is masked by strong resonant light scattering. The real radiative bulk decay times for FEs and DBEs are approximately obtained from the LO replicas.

5:00 PM

14. Observation of Well-Resolved Bound, Free, and Higher Order Excitons in AlN Epilayers Grown by Metalorganic Vapor Phase Epitaxy: Takeyoshi Onuma; Takahiro Koyama; Kei Kosaka; Keiichiro Asai; Shigeaki Sumiya; Tomohiko Shibata; Mitsubishi Tanaka; Takayuki Sota; Akira Uedono; Shigefusa Chichibu; Tohoku University; Japan Science and Technology Agency; NGK Insulators, Ltd.; Waseda University; University of Tsukuba

Distinct four bound exciton lines as well as ground-state and excited-state free exciton lines are clearly resolved in the low-temperature cathodoluminescence (CL) spectra of approximately 2-μm-thick AlN epilayers grown on (0001) Al2O3 substrates by metalorganic vapor phase epitaxy at NGK Insulators. With the decrease in the threading dislocation density from 1×1010 to 2×108 cm-2, relative intensities of characteristic deep CL bands at 4.6, 3.8, and 3.1 eV to the near-band-edge peak around 6 eV significantly decrease. Since the concentration of Al vacancies simultaneously decreases, which was confirmed by the positron annihilation measurement, those deep bands are correlated with the point defects associated with Al vacancies. From the energy difference between the ground and the first excited states, the A-exciton binding energy is determined to be 51.3 meV.

5:15 PM

15. Late News

Poster Session I

Monday, 5:30-7:00PM Room: Prefunction Area
September 17, 2007 Location: MGM Grand Hotel Conference Center

Poster Session I

Bulk Growth and HVPE

Cathodoluminescence Microscopy of High Quality Bulk-Like GaN ELOG Structures: Barbara Bastek; Frank Bertram; Juergen Christen; Christian Hennig; Eberhard Richter; Markus Weyers; Gunther Tränkle; Otto-von-Guericke-University Magdeburg; Ferdinand-Braun-Institut für Höchstfrequenztechnik

We present cathodoluminescence microscopy characterization of bulk-like c-axis grown GaN HVPE-layers. The up to 900μm thick layers were grown on patterned GaN/sapphire templates (MOVPE). Epitaxial lateral overgrowth (ELOG) was performed by HVPE over WSiN-masks consisting of a hexagonal lattice of circular openings. These layers separate from the template. CL-mappings of the bottom side of the delaminated layers show a low CL-intensity from the openings where coherent c-axis growth took place. In the immediate vicinity of the openings the CL-intensity shoots up rapidly resulting in a hexagonal glowing frame of electron-hole-plasma-luminescence. Outside these hexagons only (D1, X) emission is found. The evolution and termination of the characteristic ELOG growth domains are directly visualized in cross-sectional-CL-imaging. All layer top-side-surfaces are smooth and exhibit a sharp and bright (D1, X) luminescence at 3.472eV(FWHM=2.2meV) evidencing that the layers are completely strain free. This emission from the top is very homogeneous showing lateral fluctuation σL=0.3meV.

Direct Growth of InN and InGaN on Sapphire Substrates by HVPE: Jai Weon Jean; Sanghwa Lee; Taegeon Oh; Hyeokmin Choe; Yuri Sohn; Chinkyu Kim; Kyunghee University

InN and InGaN were directly grown on 0.3°-miscut (toward M-plane) c-plane sapphire substrates by hydride vapor phase epitaxy (HVPE) and their growth characteristics were investigated by utilizing x-ray scattering. Depending on the various growth parameters, the formation of lnN and InGaN was sensitively influenced. Six samples were grown by changing HCl flow rate, the substrate temperature and Ga and In source temperature and all
the samples were pretreated with NH₃ for 23 seconds. By increasing the flow rate from 10 sccm to 20 sccm, InGaN phase as well as InN was observed. On the other hand, when the substrate temperature was raised from 680 to 760 °C, the increased substrate temperature dramatically suppressed the formation of InN. A similar behavior was observed for the samples grown with different substrate temperature. By decreasing the source zone temperature from 450 to 420 °C, InGaN instead of InN was preferentially grown.

**Growth of Single Crystalline GaN from Chlorine-Free Gas Phase:** Hans-Joachim Rost1; Dietmar Siche1; Klaus Böttcher1; Daniela Gogova1; Roberto Fornari1; 1Institute for Crystal Growth

This work is focused on the development of GaN bulk growth to overcome restrictions of the established HVPE method. Evaporated Ga is transported by carrier gas to the substrate where it reacts with atomic nitrogen from the thermal ammonia decomposition to form GaN at temperatures of 1000 – 1300 °C and pressures of 200 – 800 hPa. To prove the methods potential, 1 mm thick polycrystalline layers were deposited on the seed holder with rates up to 50 μm/h. Numerical simulations of temperature-, flow- and concentration field of the gas species were used to optimize crucible geometry and growth regime. It was found experimentally that in addition to temperature, total pressure and ammonia flow other parameters like source composition, crucible material and flow conditions near the substrate may affect seeding, growth rate and layer quality. First epitaxial layers up to 250μm thickness were successfully grown on different bulk and template substrates.

**Growth Optimization of Thin GaN Layer Grown by HVPE:** Denis Martin1; Tiankai Zhu1; Nicolas Grandjean1; 1Ecole Polytechnique Federale de Lausanne

Thin GaN layers grown by hydride vapor phase epitaxy (HVPE) are attractive for the use as templates and for the growth of single run GaN quasi-substrates. In this work, we investigate two important steps used for the growth of thin GaN layers directly on sapphire. First is the temperature ramping rate during the nucleation layer recrystallization in a horizontal HVPE reactor and second is the planarization process for the development of a fully coalesced layer less than 10μm. We found that the temperature ramping rate applied during the nucleation layer recrystallization step does not limit the structural quality of the GaN material and can be as low as 10°C/min. Furthermore, fast planarization of the high temperature GaN layer is obtained by inserting a low-pressure growth step. Dislocation density can be reduced in the low 10⁶ cm⁻² by controlling this step while maintaining a crack free layer.

**Increase in the Growth Rate of GaN Single Crystals Grown by Gallium Hydride Vapor Phase Epitaxy Method:** Manomo Imade1; Northide Yamada1; Yoshihiro Kitano1; Fumio Kawamura1; Masashi Yoshimura1; Yasuo Kitaoka1; Yukote Kuri1; Takatomo Sasaki1; Osaka University

A dependence of gallium hydride (GaHx: x=1, 2, 3) production on the growth rate of GaN crystals has been performed by the software “Virtual Reactor” provided by STR, Inc. The heat transfer, reactive species transport, and their chemical interaction at the reactive surfaces are considered self-consistently. The major focus of the study is made on a high growth rate maintaining, V/III ratio control, parasitic deposition on the reactor walls, and crystal shape evolution. Intentional variation of the growth parameters, like temperature, precursor flow rates, and the seed-source gap, provides an effective way for stabilization and optimization of the long-term growth conditions. Special attention is given to predict the thermoelastic stress and threading dislocation density in the growing crystals, as the factors largely affecting the crystal quality. Spe-cific features of AIN and GaN crystal growth in vertical reactors are discussed in detail in terms of simulation.

**Liquid Phase Epitaxy of GaN on MOCVD GaN/Sapphire and HVPE Free-Standing Substrates under High Nitrogen Pressure:** Michal Bockowski1; 1Institute of High Pressure Physics

The liquid phase epitaxy of GaN on one- and two-inch MOCVD sapphire/ GaN templates and HVPE free-standing substrates by high pressure solution method will be presented. The crystallization on patterned substrates with variety of TiN masks will be reported in details. The growth modes in normal and lateral directions will be analyzed. The defect selective etching will be used to state the average dislocation density on the surface of laterally overgrown material. The finite element calculation will be implemented for modeling the convective transport in liquid gallium. The stream lines, convectional flow velocity vectors and isotherm lines in liquid metal will be determined based on experimentally measured temperatures. The effect of seed, crucible wall and baffle for convection in liquid metal will be analyzed. It will be shown the baffle plate allows reducing the convectional flow close to the seed and obtaining macroscopically flat growth of GaN from the liquid phase.

**Migration-Enhanced-Hydride-Vapor-Phase-Epitaxy of GaN on Sapphire Substrates:** Sanghwa Lee1; Hyecikmin Choel1; Taegeon Oh1; Jai Woen Jein1; Yori Sohn1; Chinkyo Kim1; 1Department of Physics, Kyunghee University

One of the promising methods to fabricate a free-standing GaN substrate is hydride vapor phase epitaxy, but its fast growth rate is not very advantageous during nucleation process. In order to reliably control the size and density of the nucleated islands migration-enhancement method was applied to HVPE. GaN films were directly grown on c-plane sapphire substrates at 1050 °C without any low-temperature nucleation layers. To investigate the effect of migration, the nucleation layers of GaN were grown with different duration of growth interruptions. HCl and NH₃ gases were simultaneously introduced into the reactor for 5 sec and gas supply was interrupted for 30 sec, 60 sec and 120 sec, respectively. These growth and migration processes were repeated 5 times. The increased migration time decreased the density of nucleated islands and improved the surface morphology dramatically. Our results suggest that the nucleation characteristics of GaN could be controlled by altering migration time.

**Modeling of III-Nitride Bulk Crystal Growth from the Vapor Phase:** Mark Ramn1; Maxim Bogdanov1; Sergey Karpov1; Alexey Kulik1; 1Semiconductor Technology Research, Inc.; 1‘Soft-Impact, Ltd.

Simulation of PVT growth of AIN and HVPE growth of GaN bulk crystals has been per-formed by the software “Virtual Reactor” provided by STR, Inc. The heat transfer, reactive species transport, and their chemical interaction at the reactive surfaces are considered self-consistently. The major focus of the study is made on a high growth rate maintaining, V/III ratio control, parasitic deposition on the reactor walls, and crystal shape evolution. Intentional variation of the growth parameters, like temperature, precursor flow rates, and the seed-source gap, provides an effective way for stabilization and optimization of the long-term growth conditions. Special attention is given to predict the thermoelastic stress and threading dislocation density in the growing crystals, as the factors largely affecting the crystal quality. Spe-cific features of AIN and GaN crystal growth in vertical reactors are discussed in detail in terms of simulation.
The Effect of Additive of Carbon into the Na Flux on the Growth of GaN Single Crystals: Masaki Tango; Yoshihiro Kitano; Fumio Kawamura; Masashi Yoshimura; Yasuo Kitaoka; Yusuke Mori; Takatomo Sasaki; Osaka University

We attempted an increase in the growth rate of bulk GaN single crystals in Na flux method. We have already reported some disadvantages in this method including a low growth rate. A generation of poly-crystals near gas-liquid interface lowers the growth rate because nitrogen prefers to be consumed by the growth of poly-crystals rather than the liquid phase epitaxy (LPE). In order to improve the growth rate, some attempts can be nominated: applying a thermal convection, addition of specific impurity and so on. In this study, we examined the addition of carbon into the Ga-Na mixed melt for the purpose of preventing generation of poly-crystals. Remarkable effect of the carbon on suppression of poly-crystals could be confirmed, which enabled to increase the growth rate drastically. Over 20 mm/h which could be attained in this study is considered enough for an industrial applications.

The Effects of Growth Temperature on the Crystallinity of GaN in Gallium Hydride Vapor Phase Epitaxy Method: Norihide Yamada; Mamoru Imade; Yoshihiro Kitano; Fumio Kawamura; Masashi Yoshimura; Yasuo Kitaoka; Yusuke Mori; Takatomo Sasaki; Osaka University

High temperature growth was examined for improving the crystallinity and the surface morphology in gallium hydride vapor phase epitaxy (GaH-VPE) method. In this method, GaN crystals are synthesized using gallium hydride (GaHx=1,2,3) as a Ga source. We had already confirmed that the growth rate of GaN increased with GaHx supply and reached 68 mm/h. However, improvement of a surface morphology and crystallinity of the GaN crystal has been required. In this study, the dependence of growth temperature on the crystallinity and the surface morphology of grown crystals was investigated, resulting in achievement of the flat surface at the temperature higher than 1,150 degree. In addition, improvement of crystallinity was also realized by decreasing an impurity level in the apparatus.

Thick a-Plane GaN Epitaxial Films by HVPE on Patterned Sapphire Substrates: Byung Gao; Rakesh Jain; Jianping Zhang; Jinwei Yang; Remis Gaskati; Kari Liu; Michael Shur; Sensor Electronic Technology, Inc.; Remsseler Polytechnic Institute

Thick a-plane GaN films have been grown on r-plane substrate substrates by Hydride Vapor Phase Epitaxy. Maximum thickness of 50 μm a-plane GaN films with no cracks was obtained. When film thickness is more than 50 μm, large stress causes conventional sapphire substrates and epilayer to crack. Patterned sapphire substrates were used to effectively manage built-in strain in the epitaxial layer and to suppress cracking. Using this approach, crack-free layers up to 300 μm thick were grown. Wafers have been fully characterized using photoluminescence, SEM and XRD. The characterization data clearly showed higher material quality of thick layers with much stronger photoluminescence intensity. SEM showed that a-plane GaN grew in different orientations with preferred facets. For optimized growth conditions the facet growth can be suppressed and surface morphology can be improved. Detailed characterization results including carrier lifetime data will be presented.
E<sub>in</sub>-0.73 and E<sub>in</sub>-0.56 for the rf-plasma sample. The DLOS spectra are quite similar with onset energies at E<sub>i</sub>-3.28, E<sub>i</sub>-2.62, and E<sub>i</sub>-1.28, however, the rf-plasma sample shows an additional level near EC-2.94 eV. Additionally, IVT and IPE measurements reveal nearly identical barrier heights of 1.10 eV and near-ideal room temperature ideality factors between 1.02-1.08. A full analysis of the IVT characteristics will be discussed including an enhanced thermionic-field emission characteristic energy, which we speculate could be due to donor-like surface defects.

**Correlation between the Violet Luminescence Intensity and Defect Density in AlN Epilayers Grown by Ammonia-Source Molecular Beam Epitaxy: Takahiro Koyama; Mariko Sugawara; Takuya Hoshii; John Kaeding; Rajat Sharma; Shuji Nakamura; Akira Uedono; Shigefusa Chichibu; Japan Science and Technology Agency, University of Tsukuba; Tohoku University; University of California**

The intensity ratios of characteristic deep cathodoluminescence (CL) bands at 4.6, 3.8, and 3.1 eV to the near-band-edge emission at 11 K of AlN epilayers grown by ammonia-source molecular beam epitaxy are correlated with the change in S parameter of positron annihilation measurement, which represents the concentration (or size) of Al vacancies (V<sub>Al</sub>). Since the relative intensities of 3.1 eV and 3.8 eV bands increase remarkably with lowering supply ratio of ammonia to Al (V/III ratio) and growth temperature (T<sub>g</sub>), they are assigned to donor-acceptor-pair recombination associated with V<sub>Al</sub> and/or V<sub>Al</sub>-O complexes. The V<sub>Al</sub> concentration can be decreased by adjusting V/III ratio and T<sub>g</sub>. As a result, the AlN epilayers exhibiting negligible deep level emissions show fine excitonic features in the CL spectra. Since defect complexes composed ofcation vacancies (V<sub>n</sub>-X) act as nonradiative recombination centers (NRCs) in GaN and AlGaN, V<sub>n</sub>-X may act as NRCs in AlN.

**Dislocation Related Defect States in GaN Irradiated with 1 MeV Electron-Beam: Dong Uk Lee; Lim-Kyoung Ha; Jin Soak Kim; Eun Kyu Kim; Eui Kwan Koh; Il Ki Han; Hanyang University; Korea Basic Science and Technology; Korea Institute of Science and Technology**

We have studied defect states in GaN bulk material grown by hydride vapor phase epitaxy method. The undoped GaN layers were grown with different threading dislocation densities (TDDs). The A and B samples with thickness of 278 µm showed TDD of 9.0x10<sup>5</sup> cm<sup>-2</sup> and 7.2x10<sup>5</sup> cm<sup>-2</sup>, respectively, while the C sample had thickness and TDD of 257 µm and 3.4x10<sup>5</sup> cm<sup>-2</sup>, respectively. The typical defect states were measured at the acivation energy of E<sub>i</sub>-0.34 eV, E<sub>i</sub>-0.89 eV, and E<sub>i</sub>-1.06 eV, respectively. Especially, the energy state of E<sub>i</sub>-0.89 eV was considered as a dislocation related defect, because its density tended to increase as increasing TDD. These GaN samples were irradiated by electron beam with the energy of 1 MeV and dose ranges of 1x10<sup>14</sup>~10<sup>15</sup> cm<sup>-2</sup>. The defect states in electron beam irradiated samples were characterized by capacitance-voltage and deep level transient spectroscopy measurements.

**Effects of Ultraviolet Light and Visible Laser Illumination on the Charge Status of the Surface States in a AlGaN/GaN Heterostructure: Yun-Chorng Chang**

**Electricity Properties and Deep Centers in Semi-Insulating Fe-Doped Native GaN Substrates Grown by Hydride Vapor Phase Epitaxy: B. Claffin; D. Look; H. Smith; Z. Fang; William Mitchell; D. Hansen; E. Preble; K. Evans; Air Force Research Laboratory; Kyma Technologies, Inc.**

Electrical properties and deep centers in semi-insulating Fe-doped GaN substrates grown by hydride vapor phase epitaxy were characterized by thermally stimulated current (TSC) spectroscopy. Five samples from a low-Fe wafer displayed very high 300 K resistivity (>1011 ohm-cm), dominated by a center at 0.94 eV. Five traps were observed in the samples by TSC, with trap B (0.56-0.60 eV) being dominant. Some variations in both peak temperature and peak amplitude of trap B were observed. A metastable trap A at ~0.82 eV appeared after white-light illumination at 300 K. A sample with higher Fe displayed a lower 300 K resistivity (4x10<sup>9</sup> ohm-cm), dominated by a center at 0.58 eV. The largest TSC peak in this sample was trap A1, although trap B also appeared. These TSC traps are compared with deep-level-transient-spectroscopy traps reported in conductive epitaxial and bulk GaN.

**High Quality, High Efficiency and Ultrahigh In-Content InGaN QWs - The Problem of Thermal Stability: Daniel Fuhrmann; Holger Jönen; Lars Hoffmann; Heiko Bremer; Uwe Rossov; Andreas Hangleiter; Technical University Braunschweig**

InGaN/GaN quantum well structures with Indium concentrations above 30% suited for light emitters in the green and beyond have been investigated. A homogeneous indium distribution and abrupt interfaces yield very high internal quantum efficiencies of 80% and 70% for 460nm and 510nm emission wavelength, respectively. However, for high In concentrations the heterostructures are thermally less stable. This is evident from systematic studies including varied GaN cap temperatures and different post annealing procedures. For elevated temperatures we observe a reduction of the PL intensity, a broadening and a shift to higher energies of the PL lines without indication of phase separation. The reason is the soft indium-nitrogen bond, the degradation likely occurs by In interdiffusion via defects in the structures. The critical temperatures are well below those typical for p-GaN contact layer growth and thus need to be considered in device applications.

**High Resolution Laplace Deep Level Transient Spectroscopy Studies of Electron and Hole Traps in n-Type GaN: Jan Evans-Freeman; Deniz Emiroglu; Menno Kappers; Clifford McAleese; Colin Humphreys; Sheffield Hallam University; University of Cambridge**

Deep Level Transient Spectroscopy (DLTS) and Laplace DLTS (LDLTS) have been applied to MOCVD-grown n-type GaN, grown at 1020 °C on c-plane sapphire. DLTS, measured up to 600K, initially recorded three peaks due to electron emission. When the next DLTS rate window was sampled immediately afterwards, a different spectrum was obtained. A large negative peak dominated at 400K, due to hole emission. An electron trap initially present at 400K in the DLTS spectrum gradually disappeared up to a measurement temperature of 520K; beyond this the hole trap was observed. It then remained detectable by DLTS for up to one week, although cooling under bias decreased its intensity severely. LDLTS reveals that this hole trap is not a simple point defect, and it is discussed in the context of the V<sub>Al</sub>-O<sub>n</sub> defect. The electron traps have also been characterised by LDLTS and some are found to have complex capture kinetics.

**Improved Performance and Reliability of GaN Devices via Pendeo-Epitaxy: Tsvetanka Zheleva; Michael Derenge; Daniel Ewing; Pankaj Shah; Ken Jones; David Stepp; Unchul Lee; Lawrence Robins; Army Research Laboratory**

Pendeo-epitaxy as a technology is known to enable drastic reduction of the densities of structural defects in GaN over three orders of magnitude. We have used metal organic chemical vapor deposition (MOCVD) technique to grow pendeo-epitaxial (PE)-GaN, performed analysis of the morphology, structure, and electrical properties via numerous characterization techniques, and correlated the materials and electrical characteristics with the growth and processing conditions. Further, we designed and fabricated test device structures in order to investigate the improved electronic performance of the Shottky contacts and high electron mobility transistors (HEMTs) and correlate the improved devices performance with improved structural quality of the GaN material.

**Technical Program**

7th International Conference of Nitride Semiconductors
Insights into the Origin of Threading Dislocations in GaN/Al2O3 from Atomic Force Microscopy: Rachel Oliver1; Menno Kappers1; Colin Humphreys2; 1University of Cambridge

Threading dislocations (TDs) in GaN/Al2O3 are widely assumed to arise at the coalescence boundaries of misoriented islands. Using atomic force microscopy and employing an in situ SiH4-treatment to enlarge the TD pits, we have examined GaN/Al2O3 samples at various stages of the coalescence of the GaN film. Prior to coalescence, the morphology is dominated by large (~2 μm high) islands, with smaller (50 – 500 nm high) islands observed between them. Considering the (0001) surfaces of the large islands, we find no significant difference between the TD density in the boundary regions and the overall density, suggesting that TDs do not originate at coalescence boundaries. However, a TD density ~20 times higher is observed on the surfaces of the smaller islands. When these small structures are overgrown by large islands, these TDs are incorporated into the film, resulting in TD clusters, and a rise in the overall TD density.

Microscopic Lateral Overgrowth of GaN on Diamond like Carbon Masks by Physical Vapour Transport: Daniela Gogova1; Martin Albrecht1; Matthias Rossberg1; Hans-Joachim Rost1; Dietmar Siche1; Roberto Fornari1; 1Institut für Kristallzüchtung

In this paper results on microscopic lateral overgrowth by physical vapour transport will be presented. A diamond like carbon layer is deposited on a GaN/sapphire template prior to the growth of GaN layer by physical vapour transport. For deposition of the carbon layer a solid phase carbon source and NH3 were used. The diamond like carbon layer has random opening sizes that act as windows for epitaxial overgrowth in the following step. The mask is stable even at elevated temperatures. Lateral overgrowth is done by physical vapour transport of Ga, using NH3 as a nitrogen source. Layers as thick as 280 μm are obtained. Overgrowth results in a significant decrease of the threading dislocation density compared to that of the GaN/sapphire templates. Optical properties of the resulting layer are dominated by excitonic transitions.

Microstructure of Threading Dislocations Caused by Grain Boundaries in AlN on Sapphire Substrate: Masataka Imura1; Hiroki Sugimura1; Naohito Okada1; Motoaki Iwaya1; Satoshi Kaniyama1; Hiroshi Amano1; Isamu Akasaki1; Takashi Kago1; Akira Bandoh1; 1Meijo University; 2Ibiden Company, Ltd.; 3Showa-Denko K.K.

Taniyasu et al. reported AlN-based light emitting diodes (LED) with peak wavelength of 210 nm by current injection.1) As the next step, high-power and high-efficiency deep-ultraviolet (DUV) LED has been requested. However, it is difficult to fabricate high performance DUV-LED, because the performance of the current AlGaN-based DUV-LED is strongly affected by the threading dislocations due to large lattice mismatch. Transmission electron microscopy (TEM) is generally reliable technique for analyzing threading dislocations in the layers. Hence, threading dislocations in AlN analyzed by TEM is the key issues for improving device performance of AlGaN-based DUV-LED by feedback to AlN growth from TEM analysis. As a first step, we investigated the microstructure of threading dislocations, and correlations between X-ray diffraction (XRD) peak width and threading dislocation density in detail. In addition, core structure and lattice image around them were also revealed by high-resolution (HR) TEM.

Optical Signatures and Metastability of Magnesium Related Acceptors in GaN: Bo Monemar1; Plamen Paskov1; Gaila Pozina1; Peder Bergman1; Carl Hemmingson1; Hiroshi Amano1; Isamu Akasaki1; Stephan Figge1; Detlef Hommel1; Akira Usui1; 1Linköping University; 2Meijo University; 3University of Strathclyde

We have studied MOVPE grown GaN:Mg layers prepared on HVPE grown bulk GaN substrates, in order to reduce the density of dislocations to below 107 cm-2. The Mg concentration was varied up to mid 1019 cm-2. There is clear evidence of two sets of acceptors in optical spectra, both for bound and free states. The Mg acceptors exhibit metastability. They disappear with time of excitation, in favour of deeper peaks at 3.455 eV and 3.1 eV respectively. The possible relation of these optical signatures to the Mg acceptor will be discussed. CL spectra also show evidence of the pyramidal defects in highly Mg doped GaN.

Reduction of Threading Dislocations in AlGaN/AIN/SiC Epitaxial Layers by Tensile Strain in a-Axis Induced with the (AIN/GaN) Multi-Buffer-Layer: Kouichi Murakawa1; Fumio Hasegawa2; Hideo Kawanishi3; 1Kogakuin University

Control of crystal quality of AIN and AlGaN is very important for the development of UV and deep-UV LEDs and LDs. We have found that FWHM of XRC of the AlN template and AlGaN clad layers can be improved by tensile strain in a-axis introduced by the (AIN/GaN) multi-buffer layer (MBL). Furthermore, we confirmed reduction of the threading dislocations by the tensile strain directly by the TEM observation. AIN and AlGaN epitaxial layers with Al composition of 0.6-0.8 were grown by LP-MOVPE on a 6H-SiC substrate. The tensile strain in a-axis was controlled by thickness of AIN and GaN of the MBL. Edge dislocation density was one order higher than the screw dislocation density. Some of the dislocations in the AlN template make loop to terminate each other, and the dislocation density decreases with distance from the SiC substrate. It decreases more steeply for the more strained sample.

Theoretical Study of Rare Earth Point Defects in GaN: Simone Sanna1; Uwe Gerstmann1; Benjamin Hourahine1; Thomas Frauenheim1; 1Universität Bremen; 2Université Pierre et Marie Curie, Paris; 3University of Strathclyde

In the framework of the European union network Rare Earth doped Nitrides for high Brightness Electroluminescent emitters (RENiBEl), we have developed and applied theoretical techniques to simulate the behaviour of rare earth dopants in nitride materials. The Density Functional based Tight-Binding method, developed at the University of Paderborn, has been extended to include orbital dependent potentials (LDA+U and SCF-like) in attempt to model the 4f states of lanthanide impurities within a realistic crystal model. We present results of an investigation into the structural and energetic properties of rare earth point defects in GaN, considering a selection of lanthanides which are of technological relevance as phosphors for full colour displays. Rare earth substitutional and complexes formed by substitutional and N-vacancies are examined in some detail, discussing their possible role in the luminescence process. Differences in the behaviour of the single lanthanide ions are explained in terms of different 4f-shell occupation.

What Kind of Crystal Quality of AlGaN is Improved by an Alternate-Source-Feeding MOVPE or ME-MOVPE?: Eiichiro Niikura1; Koichi Murakawa1; Shoichiro Takeda1; Fumio Hasegawa2; Hideo Kawanishi3; 1Kogakuin University

The crystal quality of AlN and AlGaN layers was improved, and optical threshold pumping power of deep UV lasers was drastically reduced, by alternate-source-feeding epitaxy (ASFE) in LP-MOVPE. FWHM of XRC and TEM observation indicated that dislocation density was not changed at all by ASFE. On the other hand, blue emission of PL from the AlGaN clad layer was decreased, indicating that point defects such as Ga or Al vacancy
are reduced by the ASFE or ME-MOVPE. Furthermore, the yellow emission from GaN/AlGaN MQW grown by conventional simultaneous source feeding epitaxy (SSFE) on the ASFE AlGaN clad layer was also reduced. This fact indicates that point defects of MQW on the AlGaN clad layer with less point defects is less than that on the AlGaN clad layer with more point defects. As a result, deep UV lasing at 240nm could be achieved in our group.

**Nanostructures: Characterization**

**Energy Level Properties of InGaN/GaN Quantum Well and Quantum Dots:** Jin Soak Kim; Y.-I. Lee; L. H. Eun Kyu Kim; H.J. Kim; E. Yoon; Y. Shon; 1Hanyang University; 2Seoul National University; 3Dongguk University

The III-nitride based materials have been very interesting topics of optical device technologies for several years. Nowadays, the III-nitride technologies are going to toward the nanostructures such as quantum well (QW) and quantum dots (QDs) to improve efficiency of the optical devices. In addition to these nanostructures, these are more applicable to electronic and information devices due to their quantum effects. Confined energy levels of carriers are the most important physical properties of the QW and QD structures. Thus, characterization of these confined energy levels of the nanostructures is very important. In this study, we characterized the energy level properties of the InGaN/GaN nanostructures by using electrical measurements such as C-V, I-V and deep level spectroscopy. These methods can clarify offset of the ground state energy levels in band structure, number of confined carriers, etc. From the results, we will compare energy level properties of the QW and QDs.

**Growth and Magnetization Study of Transition Metal Doped GaN Nanostructures:** Shalini Gupta; Hun Kang; Matthew Kane; Eun-Hyun Park; Ian Ferguson; 1Georgia Institute of Technology

III-V dilute magnetic semiconductors (DMS) have attracted attention in recent years as they offer the potential to fabricate room temperature III-V devices. Transition metal doping can introduce magnetic moments into DMS, making them promising materials for spintronics applications. This work presents the MOCVD growth and characterization of optically active GaN nanostructures which have been doped with transition metal such as manganese. However, the potential of these transition metals in GaN nanostructures has yet to be explored. This work presents the MOCVD growth and characterization of optically active GaN nanostructures which have been doped with the transition metals manganese and iron for potential spintronic applications. Introduction of these transition metals in GaN nanostructures enhanced the nucleation of the nanostructures resulting in reduced lateral dimensions and increased nanostructure density. Both Ga_Mn_N and Ga_Fe_N nanostructures showed hysteresis behavior at 5K. Further SQUID measurements on Ga_Fe_N nanostructures at 300K showed a hysteresis curve with a reduced coercive filed and displayed superparamagnetic behavior. These magnetically active nanostructures provide a promising avenue for future spintronic applications.

**InN Nanorods and Nanowires Grown on Different Substrates:** Zuzanna Liliental-Weber; M. Hawridge; J. Mangum; O. Kryliouk; 1Lawrence Berkeley National Laboratory

TEM was applied to study InN nanorods grown on different planes of Al2O3, GaN, and (001) Si substrates by non-catalytic, template-free H-MOVPE. Single crystal nanorod growth was obtained on all substrates. The majority of them are of a high structural perfection and exhibit abrupt side walls. The nanorods grown on c-plane sapphire have N-growth polarity. InN nanowires grown on (001) Si and (0002) GaN in an RF heated, horizontal cold-wall MOVPE reactor. Growth parameters such as V/I III ratio, flow velocity, and surface pretreatments were investigated with respect to the NW nucleation structure and morphology. Most of them had a triangular shape with decreasing diameter toward the tip, but with a constant composition of hexagonal InN. Application of a two-step growth method (low V/III ratio followed by a higher V/III ratio) led to very long wires (up to 100 μm) with practically constant diameter and composition.
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Spatially and Spectrally Resolved Cathodoluminescence Measurements of Single GaN Nanowires and Related Nanostructures Grown by Catalyst-Free MBE: Lawrence Roberts1; Kris Bertain1; Paul Blanchard1; Norman Sanford1; John Schlager1; Mark Vaudin1; 1National Institute of Standards and Technology

Cathodoluminescence (CL) scanning electron microscopy measurements were performed on c-axis oriented, single GaN nanowires, approximately 5 μm in length and 100 to 500 nm in diameter, grown by catalyst-free molecular beam epitaxy. Features identified in low-temperature CL spectra were the excitonic peak at 3.47 eV to 3.48 eV; one- and two-phonon replica peaks at ≈ 3.39 eV and ≈ 3.30 eV; and the broad “blue” band centered at 2.8 eV to 3.0 eV. The excitonic peak was the most intense spectral feature in all cases. Spectrally resolved CL imaging confirmed that single wires gave rise to the “blue” band. In polarization-resolved measurements, the π-polarized (perpendicular to c-axis) component of the excitonic peak was observed to lie 5 meV to 10 meV lower in energy than the σ-polarized (parallel to c-axis) component. The polarization-resolved excitonic lineshapes showed large linewidths (20 meV to 30 meV) and also large wire-to-wire variations.

Synthesis and Characterization of InN Nanowires: Zili Xie1; Rong Zhang1; Chao Nie1; Xiangjian Xiu1; Ting Han1; Ruolan Jiang1; Yousouff Zheng1; 1Nanjing University

Indium nitrides (InN) is a promising but challenging semiconductor, which has the smallest effective electron mass and direct bandgap (0.6-0.7 eV), the highest mobility and saturation velocity, and the largest drift velocity at room temperature compared with all other III-nitrides. The novel properties make InN a promising material for photonic devices such as lasers, high efficiency solar cells, LEDs in the infrared light region, and so on. Many searches have been made in synthesis and property of 2D InN, but only a few works have been reported so far on 1D InN structures due to the synthesis difficulties. Indium nitrid (InN) nanowires were synthesized by chemical vapor deposition (CVD) method on sapphire substrates with the aurum spots. The structure of the products was characterized by XRD. We also have studied the crystal structures and morphologies by HRTEM equipped with selected area electron diffraction (SAED) analysis.

Nanostructures: Growth

Coalescence Overgrowth with MetalorGaNic Chemical Vapor Deposition on Molecular Beam Epitaxy Grown GaN Nano-Columns: Tsung-Yi Tang1; Yung-Sheng Chen1; Wen-Yu Shiao1; Jeng-Jie Huang1; Chi-Feng Huang1; Tzu-Chi Liu1; Kent Averett2; John Albrecht2; C. C. Yang1; 1National Taiwan University; 2Air Force Research Laboratory

GaN nano-column growth can lead to threading-dislocation free epitaxial structures. However, the subsequent coalescence growth for connecting the GaN nano-columns is needed for practical device fabrication. In this paper, we report the coalescence overgrowth with metallocorganic chemical vapor deposition of GaN nano-columns, which are grown with molecular beam epitaxy. After 700-nm overgrowth of GaN on the nano-column sample, the nano-columns are essentially well connected although some regions of poor atomic arrangement can be observed. Also, the top surface is not so smooth with an island pattern of hundred microns in scale. Based on the transmission electron microscopy (TEM) study, the overgrown GaN is also threading dislocation free. High-resolution TEM images show a thin layer of poor crystalline structure existing between the nano-columns and the overgrown layer. X-ray diffraction and photoluminescence measurements show that the crystalline quality and optical property of the overgrown layer are superior to those of the nano-columns.

Effect of the Pretreatment on the Preferred Growth Direction of GaN Nanorods: Yuri Sobh1; Sanghwa Lee1; Tai Woon Jeen1; Taegon Oh1; Hyeokmin Choe1; Chinkyoo Kim1; 1Kyunghee University

The effect of NH3 or Ga pretreatment on the preferred growth direction of GaN nanorods was investigated. GaN nanorods were directly grown on c-plane sapphire substrates (0.3°-miscut toward M-plane (10-10)) by HVPE at the temperature of 530°C for 10 minutes. Different pretreatment conditions gave rise to distinct preferred growth-directions of GaN nanorods. By controlling the valve operation, NH3 or Ga pretreatment was selectively carried out. When the substrate was pretreated either NH3 or Ga for 23 seconds, vertically oriented GaN nanorods were observed. Not like those cases, when NH3 and HCl were simultaneously supplied to the substrate, i.e., no pretreatment of NH3 or Ga, vertically oriented GaN nanorods were observed. These results revealed that the preferred growth direction of GaN nanorods was sensitively influenced by NH3 or Ga pretreatment.

Fabrication and Optical Properties of Nano-Structured Semipolar InGaN/GaN Multiple Quantum Wells on C-Plane GaN Template: Hongbo Yu1; Taeil Jung1; P. C. Kuo1; 1University of Michigan

Reduction of the internal electric field (IEF) in III-nitride quantum wells (QWs) can improve the radiative recombination efficiency [1]. It is typically achieved by growing QWs on semi-polar [2] or non-polar planes. We report a novel approach to fabricate nano-structured semi-polar (NSSP) DHs. NSSP GaN are first fabricated on a planar c-plane GaN template using in situ silane and annealing treatment (Fig. 1). InGaN/Ga multiple quantum wells (MQWs) are subsequently grown on the NSSP GaN. Excitation power dependent PL shows that the IEF is remarkably reduced (Fig. 2). From temperature dependant PL, we estimate the internal quantum efficiency (IQE) to be 30%. We expect the IQE to be improved after optimization of growth conditions. Advantages of the reported fabrication include: i) the suppression of IEF using NSSP MQWs on c-plane GaN; ii) the enhancement of the active layer area by a factor of 2 in comparison to planar MQWs.

Formation Process of the InN Nanotips: Kwang-Ru Wang1; Su-Jien Lin1; C. H. Chen1; Zhi-Wei Jiang1; Li-Wei Tien1; Y. L. Chen1; Chia-Hsue Tsai1; Li-Kuang Wang1; Min Chen1; Quark Y. S. Chen1; Jien-Wei Yeh1; T. T. Tsai1; Nyan-Hwa Tai1; 1National Tsing Hua University; 2National Sun Yat-Sen University

InN nanotips have been successfully fabricated on Si substrate using high quality InN/AlN/Si template grown by molecular beam epitaxy (MBE). The shape of the InN nanotip is quite similar to the bamboo shoots examined with scanning electron microscopy (SEM). According to the field-emission measurement, these nanotips have shown excellent properties that could be turned on under very low field condition. The lowest turn-on field measured in our system is only 1.35 V/μm and the average result is 2.05±0.5 V/μm based on the condition of 10μA/cm2 in the vacuum level of around 5x10-6 torr. In-situ monitor of the formation of the nanotip has been recorded and can be clearly shown how these InN nanotips formed during the process.

Growth and Characterization of InxGa1-xN Nanowires by MOVPE: Jose Mangum1; Olga Kryliouk1; Albert Daveydo1; Zuzanna Lilienthal-Weber1; Tim Anderson1; 1University of Florida; 2National Institute of Standards and Technology; 3Lawrence Berkeley National Laboratory

InN and InxGa1-xN nanowires (NWs) were grown on Si(100) and GaN(0002) substrates by MOVPE without using catalysts or templates. The nucleation density of the NWs can be controlled by applying various surface treatments, such as substrate nitridation and/or low temperature buffer layers. NW dimensions vary depending on the surface treatments used, however, average diameters of 100-300 nm were noticed with growth rates from 10 to 40 μm/hr. A vapor-liquid-solid (VLS) growth mechanism is proposed due to presence of In droplets at the tip of the NWs, which act as active catalysts for 1D growth. NWs were characterized by XRD, SEM, and TEM which reveals a core-shell structure grown at low V/III ratio. An oxide shell is formed on the outside of the NW after growth due to excess In on the NW walls. A sufficiently high V/III ratio prevents the oxide shell from forming.

Improved Optical Properties of AlGaN Using Periodic Structures: Hideto Miyake1; Takeharu Ishii1; Kazumasa Hiramatsu1; Atsushi Motogaito1; 1Meisei University

A0.4Ga0.6N periodic structures were fabricated on Al0.4Ga0.6N epilayers grown on AlN/sapphire templates by electron-beam (EB) lithography and by reactive ion etching (RIE) using chlorine plasma. The effects of etching depth, dot size and lattice constant on the emission intensity were investigated. It was found that for the AlGaN periodic structures with triangular lattice
patterns, which have a lattice constant of 300 nm and a dot size of 150 nm, antireflection and enhanced transmission were obtained from the deep-ultraviolet region to the visible region (240–700 nm). The emission intensity of the periodic structure also increased to about 3 times that of the structure with a smooth surface. The excellent optical properties of the periodic structure are expected to improve the performance of photo-detectors.

**Metalorganic Chemical Vapor Deposition of InGaN Layers on ZnO Substrates:** Shen-Jie Wang; Nola Li; Eun-Hyun Park; Zhe Feng; Adriana Valencia; Jeff Nause; Matthew Kane; Ian Fergusson; Georgia Institute of Technology; National Taiwan University; Cernet, Inc.

Epitaxial InGaN layers have been successfully grown on ZnO substrates by metalorganic chemical vapor deposition. The grown materials were characterized by a series of techniques, including high-resolution X-ray diffraction, atomic force microscopy, scanning electron microscopy, secondary ion mass spectrometry, optical transmission, and room temperature and temperature-dependent photoluminescence. All results showed good quality InGaN films with a wide range in composition, without In droplets. The variation of In incorporation in the InGaN layers was adjustable by changing growth temperature. AFM revealed the microstructure of the InGaN surface. SMS indicated the Zn and O diffusion occurring at the interface. The mechanisms of epitaxial growth and the inter-diffusion between InGaN and ZnO substrates are discussed. Furthermore, the phase separation suppression in InGaN layers grown on ZnO substrates with high In content is studied.

**Nanopatterning GaN with Microspheres:** W.N. Ng; X.H. Wang; C.H. Leung; T.P. Lai; Hoi Wai Choi; University of Hong Kong

We demonstrate the simple and economical solution of microsphere lithography to create nanorods and nano-islands on GaN substrates. Self-assembled hexagonal SiO2 microsphere arrays are formed on SiO2-coated GaN substrates by spreading the 500 nm particles uniformly across the wafer as a monolayer, acting as a hard-mask. The wafer is subsequently dry-etched, so that triangular nano-pores are created on the oxide layer. The pattern is finally transferred onto GaN by ICP etching. The resultant triangular nanopores, of approximately 100 nm, are laid out in an orderly fashion over regions of 500 x 500 μm. Similarly, nano-island arrays can readily be formed using a slightly modified process flow, by depositing metal through the microsphere void regions. Due to the low-dimension, strain-relaxation occurs in the heavily strained InGaN/GaN MQW. The characterization of the GaN nanopores and nano-islands will be reported in full in the complete paper, including structural and optical properties.

**Nucleation of Nanorods and the Density Control by NH3, Flow Rate:** Taegon Oh; Yuri Sohn; Hyeokmin Choe; Sanghwa Lee; Jai Weon Jean; Chinkyo Kim; Kyunghee University

Nucleation characteristics and density dependence of GaN nanorods on the NH3 flow rate were investigated. The GaN nanorods were grown on c-plane (0001) sapphire substrates by using hydride vapor phase epitaxy (HVPE). The growth temperature was about 500°C. HCl flow rate over Ga boat was 40 sccm and NH3 flow rates were 2000 sccm, respectively. Nitrogen was used as carrier gas. With increasing growth time, the density of nucleated islands increased and individual nanorods started to form. Then, the growth time was fixed to 10 min and the NH3 flow rate were varied. The sample grown with the NH3 flow rate of 5000 sccm had the similar surface morphology as the one grown with the NH3 flow rate of 2000 sccm, but with the NH3 flow rate of 7500 sccm the diameter became two times larger and individual nanorods were clearly distinguishable.

**Optical Properties of In-Rich InAlN Nanocolumns:** Junpei Kaminosu; Shunsuke Ishizawa; Akihiko Kituchi; Katsumi Kishino; Sophia University

Optical properties of the In-rich InAlN nanocolumns were investigated. The room-temperature PL peak wavelengths of InAl1-xN nanocolumns (x=0.71–1.00) ranged from 0.95 to 1.94 μm. The full-width at half-maximum of the In0.92Al0.08N spectrum was 107 meV. The Stokes-type shifts between the emission energy and the absorption edge increased linearly with increasing the In-composition and became over 400 meV at xIn=0.71. This phenomenon can relate to spatial In-fluctuation, which is brought about due to the immiscibility between AlN and InN. The temperature dependency of the PL intensity was evaluated for the In0.92Al0.08N nanocolumns. The intensity ratio between integrated PL intensities at 300 K and 7 K, I(300K)/I(7K) was 46%, possibly showing a high internal efficiency. And it could show that In-rich InAlN possesses short effective radiative and long non-radiative lifetimes due to localized radiative recombination centers as reported in lower In-content InxAl1-xN (xIn=0.25, 0.44).

**Selective Area Heteroepitaxy of Low Dimensional a-Plane and c-Plane InGaN Nanostructures by Using Pulsed MOCVD:** Vibha Jindal; James Gandrusky; Neeraj Tripathi; Mihir Tungare; Odyssey Paschos; Pradeep Haldar; Fatemeh Shahedipour-Sandvik; CNSE

High density a-plane and c-plane InGaN nanostructures have been developed by nanoscale selective area epitaxial growth using pulsed MOCVD. SiO2 was used as a mask with nano-patterning through anodic aluminum oxide template. The lateral dimensions of the pattern were controlled and varied between 20 nm to 150 nm by changing the anodization voltage and the electrolyte used. Different substrates such as a-plane GaN, c-plane GaN, r-plane Sapphire and c-plane Sapphire were utilized as template to develop InGaN nanostructures in a- and c- crystallographic directions. Under identical growth conditions, nanostructures on different templates have revealed different shapes of the nanostructures. The shape of the nanostructures on different templates is discussed with respect to the stability and growth rates of different planes. Low-temperature photoluminescence was used to determine the optical properties of the nanostructures while HR-TEM was employed to develop understanding on structural properties of InGaN nanostructures.

**Surface-Morphology Evolution of GaN Nanorods Grown by HVPE:** Hyeokmin Choe; Yuri Sohn; Sanghwa Lee; Jai Weon Jean; Chinkyo Oh; Chikyung Hee Ung

Surface-morphology evolution of GaN nanorods grown by hydride vapor phase epitaxy (HVPE) was investigated. GaN nanorods were grown on c-plane sapphire substrates with a 0.3 μm-thick layer of a-plane GaN. The growth time of these samples was set to be 10 sec, 15 sec, 1 min, 2 min, 7 min, and 15 min, respectively. The growth temperature of these samples was 510°C and the surface morphology was characterized by SEM. During the initial stage of nucleation a small density of GaN grains was formed. Up to the growth time of 1 min the grain density increased a lot, but vertically grown nanorods were not observable. By increasing growth time, the density of the grains became larger and the vertical growth rate was visibly increased. Further increase of the growth time resulted in increase in diameter and individual rods merged decreasing the overall density of the rods.

**Terahertz Spectroscopy of Vertically Aligned InN Nanorod Arrays:** Hyeong Yoon Ahn; Yun-Pu Ku; Chun-Hao Chuang; Ci-Ling Pan; Shangjr Hyeyoung Ahn; National Chiao Tung University; National Tsing Hua University

Terahertz time-domain spectroscopy (THz-TDS) and time-resolved THz spectroscopy is used to investigate THz conductivity and ultrafast carrier dynamics of vertically aligned indium nitride (InN) nanorods arrays and the InN film grown by nitrogen-plasma-assisted molecular-beam epitaxy on Si(111) substrates. The static THz conductivity of InN film obtained from THz-TDS is well fitted by the simple-Drude model, while negative imaginary conductivity of InN nanorods is reproduced better using the Drude-Smith model. The plasma frequency and the carrier relaxation time, that determine the free carrier dynamics, are obtained to be 49.7 THz and 70 fs, respectively for InN film. For the effective electron mass of 0.077m0 of InN, the Hall mobility of the InN film is extracted to be 1624 cm2/Vs, while that of the InN nanorods is 71 cm2/Vs. Time-resolved THz spectroscopy shows that the decay time constant of the photoconductivity in film is 15-fold longer than that in nanorods.
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Structural Analysis

A Comparative Study on Single and Double Channel AlGaN/GaN High Electron Mobility Transistors: Jing Yao Zheng; Der Yuh Lin; Hong Ji Lin; ‘National Changhua University of Education

We present a numerical investigation on the DC and AC characteristics of AlGaN/GaN single (SCHEMT) and double channel high electron mobility transistors (DCHEMT) using the APSYS simulation program. The performance of the DCHETM and SCHEMT is simulated and compared. The influence of polarization charge induced by spontaneous and piezoelectric charges is considered in the simulation model. The simulation results, such as the capacitance-voltage characteristic, DC current-voltage characteristic, cutoff frequency, maximum frequency and transconductance, match well with the experimental data that have been reported. The simulation results indicate that the DCHETM has better performance than SCHEMT. The effect of the barrier layer thicknesses between the two channels on the transconductance has been studied. We find that a flatter profile of the transconductance and a widened operation range can be achieved by optimizing the barrier layer thicknesses. A comprehensive simulation and an optimizing design for DCHETMs is presented and discussed.

Anomalous X-Ray Reflectivity Study of InGaN/GaN Multi-Quantum Well Structure: Sung Pyo Lee; Do Young Noh; Sang Won Kang; Hyo Jung Kim; Yon-Chun Kim; ‘Gwangju Institute of Science and Technology; ‘Samsung Electro-Mechanics

We present an anomalous x-ray reflectivity study to characterize the interfacial structure of InGaN/GaN multiple quantum well (MQW) structure. Using synchrotron radiation, the specular x-ray reflectivity(SXR) and the longitudinal diffuse reflectivity(LDR) are measured at various x-ray energies across the Ga absorption edge, 10.373 keV. At small angles, the total reflection from MQWs was dominated by the diffuse intensity, and the SXR component was hidden under the LDR component. Characteristic Bragg reflections corresponding to the well-barrier period of the MQW are clearly observed in the LDR, which indicates that the MQW interfaces are very well correlated. In addition, the anomalous x-ray reflectivity (AXR), the energy dependence of x-ray reflectivity curve, was measured to determine the exact chemical profiles as well as the layer thickness of each well and barrier.

Assessment of Scanning Spreading Resistance Microscopy for Application to n-Type GaN: Joy Sumner; Rachel Oliver; Menno Kappers; Colin Humphreys; ‘University of Cambridge

Scanning spreading resistance microscopy (SSRM) can be used to study carrier concentrations in GaN-based semiconductors. However, the basic principles underpinning its responses are not yet fully understood. Thus we have grown appropriate Si-doped multilayers to test SSRM’s spatial resolution and carrier concentration sensitivity. For samples with no undoped regions, layers with dopant concentrations from $1 \times 10^{18}$ cm$^{-3}$ to $2.5 \times 10^{19}$ cm$^{-3}$ may be distinguished, but the relationship between SSRM signal, applied bias and dopant level is complex. However, in samples with undoped layers it is very difficult to obtain any SSRM signal. SSRM is only able to distinguish between different dopant levels for biases in the range of $-2$ to $7$ V, above which damage to the sample occurs. In terms of resolution, feature sizes down to 50nm were routinely resolved and SSRM sometimes had the ability to resolve features down to 10nm with the observed performance being strongly dependent on the probe used.

Comparison between Extended Microtunnels along Different Crystal Orientations in GaN: Hsin-Hsiung Huang; Pei-Lun Wai; Hung-Yu Zeng; Feng-Ke Hsiao; Po-Chun Liu; Tung-Wei Chi; Jenq-Dar Tsay; Wei-I Lee; ‘National Chiao Tung University; ‘Industrial Technology Research Institute

It has been demonstrated before that extended microtunnels (EMT) extending beyond hundreds of microns with triangular cross sections in thick GaN films can be easily fabricated using wet chemical etch on specially designed epitaxially lateral overgrowth (ELOG) structures. In the present study, extended microtunnels (EMTs) along the <1-100> direction and along the <11-20> direction were fabricated and compared. For tunnels along the <1-100> direction, the [11-22] family of planes were the etch stop planes, while for tunnels along the <11-20> direction, the [10-11] family of planes were the more stable planes. The activation energies of wet chemical etch for the [11-22] family of planes and the [10-11] planes were determined to be 13.8 and 3.9 kcal mol$^{-1}$, respectively. As a result, the depths of the tunnels along the <1-100> direction were more than twice the depths of the tunnels along the <11-20> direction. The highest etch rate of the tunnels along the axial direction can reach 1000 μm/hr, which is believed to be the highest etch rate of GaN ever reported.

Dislocation Reduction in an AlGaN Layer Grown Using a GaN Interlayer on a High Temperature AlN Buffer: Jie Bai; T. Wang; K. B. Lee; P. J. Parbrook; A. G. Cullis; ‘University of Sheffield

A significant dislocation reduction is achieved in an AlGaN layer grown on an AlN buffer by introducing a thin GaN interlayer. The mechanisms for the dislocation reduction are explored by transmission electron microscopy, energy-dispersive x-ray spectroscopy, atomic force microscopy and micro-Raman spectroscopy. The GaN interlayer takes the form of platelets on the AlN. The mechanisms of dislocation reduction in the platelet area and the area between the platelets are different. In the GaN platelets, due to the large misfit strain, the threading dislocations (TDs) in the AlN layer migrate into the interface and annihilate with each other. However, the GaN between the platelets is highly strained so that a higher density of TDs from AlN is incorporated into the upper layer. The coalescing of the platelets induced by the AlGaN growth makes the TDs in the areas between the platelets assemble and annihilate, resulting in additional dislocation reduction.

Electronic and Chemical Properties of Strained GaN/InGaN Heterostructure: Seong Ran Jeon; Jong Hyub Baek; Ja Soon Jang; ‘Korea Photonics Technology Institute; ‘State University of New Jersey, Department of Electrical and Computer Engineering

Strain-induced spontaneous polarization and external dopant-induced piezoelectric polarization in strained layers give rise to an increase of the sheet carrier concentration for ohmic contact and an enhancement of short-circuit barrier height for schottky one. Although strained InGaN/GaN layers have been extensively studied to obtain good contact layer in the light emitting diodes, only a few studies on electrical and electronic energy band characteristics of strained u-GaN/InGaN layers have been reported so far. In this study, we have investigated polarization field effect on the electrical and spectroscopic characteristics at strained u-GaN(u)-InGaN layer before and after Si doping. It is shown that polarization charges originated from two dimensional electron gas sheet concentration is considerably dependent on the growth temperature, and surface Fermi level is pinned irrespective of growth conditions due to highly accumulated surface defects.

High-Resolution Rutherford Backscattering Spectrometry for InAlGaN/AlGaN Single Quantum Well Structure: Hiroaki Sakuta; Takeshi Fukui; Tsutomu Miyachi; Satoshi Kuraki; Tsunemasu Taguchi; ‘Yamaguchi University

InAlGaN/AlGaN single quantum well structure has been studied by means of high-resolution Rutherford backscattering spectrometry (HRBS). The composition of each layer has been estimated to be In$_{x}$Al$_{1-x}$Ga$_{1-y}$N from HRBS measurement. The channeling measurements show the high degree of the crystalline perfection that can be achieved in such epitaxial layers from the normalized yield of 3.3% in the direction of the <1-102> axis. The channeling spectrum also shows atomic disorder differences between InAlGaN epilayer and AlGaN epilayer from comparing the aluminum and gallium minimum yields of each layer, respectively. Furthermore aluminum minimum yields are larger than indium minimum yields in the AlGaN layer. It is indicated that the difference of the lattice displacement by the thermal vibration or the atomic displacement. In this conference, we will present the original issues on subjects, which the atomic order evaluation of each atom in InAlGaN/AlGaN SQW structure by the HRBS channeling.
Inclusions in InN Imaged by HRTEM: Til Bartel; Petra Specht; Christian Kisielowski; TU Berlin; Lawrence Berkeley National Laboratory

The bandgap of InN is the subject of intense controversy ever since evidence of a transition around 0.7-0.9 eV was found in luminescence and absorption measurements a few years ago. However several groups pointed out, that these measurements could be explained by defect states or inclusions in the material. In particular, it has been shown theoretically, that metallic InN inclusions can cause Mie resonances that could cause the observed infrared transition. We present HRTEM images of hexagonal InN layers that show inclusions of a few nanometers in size that could cause such resonance. These inclusions are unstable under electron beam exposure, which leads to the dilution of the cluster and to a reconstruction of the InN lattice. Interestingly, InN does not show beam damage after prolonged irradiation, but locally reconstructs into a cubic lattice. Strain relaxation and inclusion of In-N is proposed as an explanation for this effect.

In-Situ X-Ray Diffraction during MOCVD of III-Nitrides: Clemens Simbrunner; Tian Li; Matthias Wegscheider; Andrea Navarro-Quezada; Martin Quast; Alberto Bonanni; Alexander Kharchenko; JürgenBethke; Klaus Lischka; Helmut Sitter; Johannes Kepler Universität Linz; PANalytical B. V.; University of Paderborn

We implemented, to our knowledge the first time, in-situ x-ray diffraction (IXRD) as a real-time process-control tool for the metalorganic chemical vapor deposition of III-nitrides using a PANalytical standard Cu x-ray source. Presently, we are able to measure in-situ x-ray diffraction and spectroscopic ellipsometry on rotating samples during the deposition process in our AIXTRON 200 RF-S reactor. Due to the unique geometry of the reactor, IXRD can be performed simultaneously to spectroscopic ellipsometry. In particular, we report on the potential of IXRD as an in-situ monitoring tool, during the deposition of III-nitride hetero- and superlattice (SL)-structures, yielding SL periodicity and composition. Furthermore, we present a kinetic analysis of the relaxation processes during the SL-deposition which is yielded by in-situ reciprocal space mapping.

Interface Migration in Selective Area Grown Multi-Facet Ridges with InGaN/GaN Multiple Quantum Wells Studied by Microbeam X-Ray Diffraction: Andrei Sirento; P. Bonanno; S. O’Malley; A. Kazimirov; Z.-H. Cai; T. Wunderer; B. Neubert; P. Brückner; F. Scholz; New Jersey Institute of Technology; Cornell High Energy Synchrotron Source; Advanced Photon Source; University of Ulm

Structural properties of multi-facet ridges with InGaN/GaN multiple quantum wells (MQW) produced by MOVPE in the regime of selective area growth have been studied using x-ray diffraction and interpreted in terms of the interface migration of precursors. Samples consisted of arrays of GaN-based triangular and trapezoidal ridges with the lateral size of 4, 6, and 8 microns and the sidewalls terminated by \{11.2\} or \{1-1.1\} facets. Microbeam synchrotron radiation at CHESS and APS has been utilized for high-resolution x-ray diffraction measurements and reciprocal space mapping (RSM) of MQW structures grown both at the top \{00.1\} and sidewall facets of the ridges. Using focused synchrotron radiation with the beamsize of 250 nm, we observed a few degree tilt of the \{00.1\} crystallographic planes for the GaN cap layers grown on the sidewalls of trapezoidal ridges and variation of the global strain and MQW period along the sidewalls of the triangular ridges.

Investigation of Bonds Length in Uncapped and Capped InGaN/GaN Quantum Dots by EXAFS: Edita Piskorska; Michael Siebert; Thomas Schmidt; Julie O. Cross; Tomohiro Yamaguchi; Jens Falta; Detlef Hommel; Polish Academy of Science, Institute of Physics; University of Bremen, Institute of Solid State Physics; Advanced Photon Source

The investigated InGaN quantum dots have the wurtzite structure. The cation sites are randomly occupied by In and Ga atoms and all the anion sites by N atoms. Due to the large difference between the Ga–N and In–N bond lengths, the atom positions are considered to fluctuate from the perfect lattice sites, leaving a bond-length distortion and causing a high degree of atomic ordering. Moreover, the GaN cap layer of InGaN quantum dots introduce changes in chemical compositions of dots and introduce additional strain. The capping process can also lead to a dissolution of the dots and form a more or less homogeneous layer with properties of a quantum well. Therefore the extended x-ray absorption fine structure (EXAFS) due to a precision in the determination of interatomic distances was used to obtain an information on the bond length In–N, In–Ga and In–N in InGaN quantum dots.
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Morphological Study of Non-Polar (11-20) GaN Grown on r-Plane (1-102) Sapphire: Carol Johnston; Menno Kappers; Jonathan Barnard; Colin Humphreys; Cambridge University

In order to grow high quality non-polar GaN-based LED structures it is important to understand the mechanism of GaN growth by MOVPE on r-plane i.e. (1-102) sapphire. In this work, (11-20) GaN epilayers have been characterised at three stages of growth using XRD, TEM and AFM. The growth conditions were such that 3D islands formed initially then coalesced to form a smooth film. XRD omega scans revealed an anisotropy in the layers with respect to the [1-100] and [0001] axes. AFM scans show that the islands are elongated along the c-axis. TEM has been used to analyse the layers further. A high density of stacking faults (5x10^5 cm^-2) and threading dislocations (4x10^10 cm^-2) was found. In island samples, defects run perpendicular and at ~60° to the sapphire surface. Methods to reduce this defect density and improve the quality of these non-polar layers will be discussed.

Plastic Relaxation in Wurtzite InGaN/GaN Heteroepitaxial Systems: Jin Mei; Rong Liu; Sridhar Srinivason; Fernando Ponce; Hiromasa Omiya; Takeshi Mukai; Arizona State University; Nichia Corporation

Different plastic relaxation processes of InGaN/GaN heteroepitaxial systems occur depending on the surface geometry and threading dislocation density of underlying templates. Generation of misfit dislocation arrays via slip on the secondary {11-22}<11-23> slip system happens in In_{x}Ga_{1-x}N epilayers (x>0.11) on low-dislocation-density free-standing GaN substrates but not on high-dislocation-density sapphire substrates. This slip process is also found to induce a cross-hatch pattern on the InGaN surface. On the other hand, presence of surface indentations intercepting the InGaN/GaN interface leads to almost complete strain relaxation via slip on the main (0001)<11-20> slip system, regardless of the threading dislocation density in the substrates. This is observed in In_{x}Ga_{1-x}N films on free-standing GaN substrates with deep surface pits (x=0.07) as well as on high-dislocation-density GaN/sapphire templates (x=0.2) with mesa structures formed in GaN layer. Understanding the strain relaxation mechanisms in InGaN heteroepitaxy is helpful for growth of high-quality, fully-relaxed, InGaN films for longer-wavelength applications.

Structural Characterisation of GaN Directly Grown on a Ge-(111) Substrate: Yucheng Zhang; Clifford McAlessé; Huxun Xu; Colin Humphreys; Ruben Lictén; S. Degroote; G. Borghs; University of Cambridge; Eletro-University Microelectronics Center

GaN epiayers have recently been grown directly on a Ge-(111) substrate. Despite the large lattice mismatch, the initial results are very encouraging. This paper presents the work on characterisation of the GaN structure using a combination of techniques including optical microscopy (OM), X-ray diffraction (XRD), atomic force microscopy (AFM) and transmission electron microscopy (TEM). Two features have been identified and investigated. One feature has a triangle shape, as observed in OM plan-view imaging, and is essentially a faceted void in Ge extending from the interface into the substrate. Another feature is the formation of domains due to the misorientation of GaN relative to the Ge substrate with a twist of ±4° around the GaN-[0002] axis. Growth mechanisms based on these observations will be discussed.

Structural Defects in Eu Doped GaN Observed by Transmission Electron Microscope: Jongwoon Seo; Junji Sawahata; Masaharu Mitome; Katsuhito Nakamura; Hidekazu Kobatake; Akira Hakomori; Kenji Hiraga; Tohoku University; Tokuyama Corporation

Eu doped GaN has been grown by molecular beam epitaxy on sapphire(0001) substrates with the Eu concentration from 0.5 at% to 7.5 at% were studied by transmission electron microscope (TEM). A conversion from hexagonal single crystal to polycrystalline structure was observed at the Eu concentration of about 3 at%, at which strong Eu-related luminescence was obtained. At the Eu concentration of about 3 at%, high density of stacking fault and cubic phase were observed. The formation of the stacking fault and cubic phase may be due to the strain relaxation caused by the incorporation of Eu whose ionic radius is 1.5 times larger than that of Ga. The formation of the stacking fault and cubic phase may be responsible for the conversion from single crystal to polycrystalline structure of Eu doped GaN.

Unintentional Doping in GaN Assessed by Scanning Capacitance Microscopy: Joy Sumner; Subblankan Das Bakshi; Rachel Oliver; Menno Kappers; Colin Humphreys; University of Cambridge

Scanning Capacitance Microscopy (SCM), a carrier concentration sensitive atomic force microscopy technique, provides an ideal means to locate unintentionally-doped material within GaN structures, for example at GaN/sapphire interfaces and in Epitaxial Lateral Overgrowth (ELOG) samples. Using SCM we observe a region of unintentional n-type conductivity in the GaN adjacent to the GaN/sapphire interface. The variation in the width of this region and its carrier concentration with the coalescence time during GaN epilayer growth may be assessed. Quantification of carrier concentrations may be achieved by comparison with a calibration structure grown on the top GaN surface. Various doped regions are also observed in ELOG samples. GaN initially grows through the mask forming faceted stripes, which exhibit n-type conductivity. Magnesium is used to enhance coalescence, resulting in p-type regions. The top layer, grown following coalescence, appears non-conducting. Details of the carrier concentration may again be quantified using a calibration structure.

X-Ray Diffraction Study on GaN Nano-Column Overgrowth with Molecular Beam Epitaxy: Wen-Yu Shiao; Jeng-Jie Huang; Tsung-Yi Tang; Yung-Sheng Chen; Kent Averett; John Albrecht; C. C. Yang; National Taiwan University; Air Force Research Laboratory

Reciprocal space mapping (RSM) on the (105) plane of threading-dislocation free GaN nano-columns and their overgrowth layers was performed to compare the tilt, twist, and strain distributions of the samples grown with molecular beam epitaxy (MBE) of different conditions on sapphire and silicon substrates. From the features of RSM, it is found that the crystalline tilt is stronger in the nano-columns grown on sapphire while those grown on silicon have stronger twists. After the overgrowth with MBE, more features appear in RSM indicating that strain distribution in the overgrown layer is quite non-uniform. Comparisons of the X-ray diffraction results between the overgrown samples of the GaN nano-columns with MBE and metalorganic chemical vapor deposition (MOCVD) are made. Based on the measurements, the overgrown layer with MOCVD has a slightly higher crystalline quality when compared with that with MBE. Also, the overgrown layer generally has a higher quality than the nano-columns.

Structure

AIN Thin Film Prepared by Sapphire Nitridation Method: Hiroyuki Fukuyama; Katsuhito Nakamura; Hidekazu Kobatake; Akira Hakomori; Kenji Hiraga; Tohoku University; Tokuyama Corporation

In the present study, high-quality single crystalline AIN films have been fabricated by nitriding sapphire by N2-CO gas mixtures with a precise control of driving force of the nitridation reaction based on the chemical potential diagram of the AIN-Al2O3-C-N2-CO system at elevated temperatures. The nitridation reaction is a complex chemical reaction and depends on the driving force of the reaction and the chemical potential of the reactants. The AIN film has the values of full-width at half-maximum (FWHM) of rocking curves using (0002) and (1-100) planes of AIN for tilt and twist components as follows: Tilt = 216 arcsec and twist = 292 arcsec. More details will be presented at the conference.

AIn/GaN Superlattice Quality Improvement by Using Multiple Superlattice Structure: Martin Vies; Kazuki Hagihara; Shinya Nakagawa; Yoku Inoue; Akihiro Ishida; Shizuoka University

We report on an improvement of structural and morphological quality of AIN/GaN superlattices when the multiple superlattice structure (MSL) is used. Such a structure contains a few of AIN/GaN simple superlattices with a small number of periods separated by thick GaN layer. Hot wall epitaxy technique (HWE) was used to grow these structures and atomic force microscopy (AFM) as well as X-ray diffraction measurements were used to
obtain the information about their structural and morphological properties. According to AFM measurements, the number of threading dislocations and the surface roughness were decreased compared to the simple superlattice. X-ray rocking curve (XRC) measurements exhibit narrower peaks, so the full width at half maximum (FWHM) of the 0th superlattice peak was decreased by 37%.

Control of Polarity and Reduction of Threading Dislocation Density (TDD) of AlN/AlGaN Buffer on Sapphire by Using TMAI Pulse Supply Method: Norimichi Noguchi; Tomoaki Ohashi; Norihiko Kamata; Hideki Hirayama; RIKEN; Saitama University
We fabricated high-quality AlN/AlGaN buffers for ultraviolet (UV) light-emitting diodes (LEDs) on sapphire using TMAI pulse supply method. We succeeded in the control of polarity and obtained stable Ga (+) polarity using this method, which was confirmed by observing the change of surface morphology. We also demonstrated this method is very effective for reducing threading dislocation density (TDD). TDD was reduced to be approximately 1/3, and the minimum TDD estimated from the surface pit density was approximately 1×10^4 cm^-2. We observed TDs are bended and disappeared in the AlGaN & TMAI pulse supply layer from the cross-sectional transmission electron microscope (TEM) image. We fabricated 350 nm-band InAlGaN multi-quantum well (MQW) UV-LED on the high-quality template using TMAI pulse supply method. Output power of the LED was 2.0 mW under RT CW operation, which was operationally 1.7 times larger compared with the case using conventional AlN/AlGaN template.

Dislocation Generation at the Coalescence of Aluminum Nitride Lateral Epitaxy on Shallow-Grooved Sapphire Substrates: Jiu Mei; Fernando Ponce; R. S. Qahid Facede; Asif Khan; University of South Carolina
The joining of defect-free AlN stripes has been observed to trigger the generation of a large density of threading dislocations in the vicinity of the coalescence point. The AlN structure was grown by pulsed lateral epitaxy on shallow-grooved sapphire substrates. In the pre-coalescence stage, the dislocation density in the lateral epitaxial region (~10^14 cm^-2) is over two orders of magnitude less than in standard c-plane epitaxy. We have found that crystalline quality of epitaxial AlN can be grown directly on sapphire are 78 arcsec and 1314 arcsec for 0002 and 10-12 diffractions, respectively. We have also found that high quality AlN can be grown even at room temperature with this technique. These results indicate that the use of PSD is quite promising for large-area low-cost preparation of substrates for future UV LEDs.

Epitaxial Growth of III Nitrides on Rh(111) UV Mirrors: Shigeru Inoue; Koichiro Okamoto; Takayuki Nakano; Jitsuo Ohta; Hiroshi Fujioka; University of Tokyo; Kanagawa Academy of Science and Technology
We have succeeded in epitaxial growth of group III nitrides on mirror polished single crystalline Rh(111) substrates using a low temperature growth technique by pulsed laser deposition (PLD). Although growth of AlN films on Rh at 750°C results in formation of poly-crystalline materials, reduction in growth temperature down to 450°C makes it possible to grow high quality AlN with an in-plane epitaxial relationship of AlN(11-20)/Rh[1-10]. This success can be attributed to the suppression of the interfacial reactions between AlN and Rh. We have also confirmed that high quality GaN can be grown on the AlN/Rh structure. Since Rh exhibits the high thermal conductivity and high reflectivity even in the ultraviolet region (~70% at 300 nm), this technique makes Rh(111) quite promising for heat-dissipative substrates of future UV LEDs.

Epitaxial Growth of High Quality AlN by Pulsed Sputtering Deposition: Takayuki Nakano; Akira Aoyama; Yasuhiro Goto; Koichiro Okamoto; Sigeru Inoue; Hiroshi Fujioka; Kanagawa Academy of Science and Technology; University of Tokyo
We have grown AlN films on ALO_x (0001) and ZnO (000-1) substrates by pulsed sputtering deposition (PSD), and investigated their structural properties. We have found that crystalline quality of epitaxial AlN films can be dramatically improved by the reduction in the pulse width and pulse frequency, which is probably attributed to the enhanced migration of Al atoms on the surface. FWHM values of X-ray rocking curves for AlN grown directly on sapphire are 78 arcsec and 1314 arcsec for 0002 and 10-12 diffractions, respectively. We have also found that high quality AlN can be grown even at room temperature with this technique. These results indicate that the use of PSD is quite promising for large-area low-cost preparation of high quality AlN for future UV LEDs.

III-Nitride Device Growth: Quantitative Analysis of In-Situ Wafer Bowing: Arne Knauuer; Frank Brunner; Thobias Schenk; M. Borasio; Elisabeth Steinmetz; Markus Weyers; Thomas Zettler; Ferdinand-Braun-Institut für Höchstfrequenztechnik; LayTec GmbH
Wafer bowing measurements in combination with temperature and reflectance measurements have been recently developed into an efficient tool for empirical III-Nitride epitaxial growth optimization. This paper is going beyond: we focus on a quantitative analysis of wafer bowing throughout the full AlGaN/GaN layered structure. Starting from the basic models of film stress causing wafer bowing we describe the physical effects and models to be included for a quantitative analysis. The contributions of vertical temperature gradients, composition dependent lattice constants and thermal expansion coefficients will be separated. It will be shown that for AlGaN/GaN growth on sapphire the lattice-mismatch induced stress can be described accurately by combining the simple Stoney equation with the concept of a GaN-sapphire coincidence lattice. This enables an accurate determination of AlGaN and InGaN lattice constants of bulk layers and AlxGa1-xN/GaN super-lattices already during growth in MOVPE.

Improvement of GaN Quality Prepared by Hydride Vapor Phase Epitaxy Using Air-Bridged Growth Technique: Hsin-Hsiung Huang; Po-Chun Liu; Ting-Wei Chi; Ming-Zheng Hsu; Yu-Lin Chang; Li-Wei Tu; Jeng-Dar Tsay; Wei-I Lee; National Chiao Tung University; Industrial Technology Research Institute; Department of Physics and Center for Nanoscience and Nanotechnology, National Sun Yat-Sen University
In the present study, a specially designed pendediagonal epitaxial lateral overgrowth process, called air-bridged growth, has been developed to grow...
**Technical Program**

thick GaN layers using hydride vapor phase epitaxy technique (HVPE). The quality of the GaN layers grown by this technique has been compared to GaN layers prepared by a more conventional pendeo growth process. The quality of GaN layers prepared by both techniques were examined by scanning electron microscopy (SEM), cathodoluminescence (CL) spectra and images, x-ray diffraction (XRD), and etch pit density (EPD) measurements. It is shown that the air-bridged growth process can effectively reduce the dislocation density from $10^8$ cm$^{-2}$ to $10^7$ cm$^{-2}$. Other characterizations also indicate superior quality of the air-bridged structure over the more conventional pendeo structure.

InN Layers Grown by the HVPE: Alexander Syrkin; Vladimir Ivantsov; Alexander Usikov; Vladimir Dmitriev; Gaëtan Chambard; Pierre Rutervera; Albert Davydov; Siddarth Sundaresan; Evgenii Lutsenko; A. Mudry; TDI, Inc.; CNRS-ENSICAEN; National Institute of Standards and Technology; George Mason University; Institute of Physics, National Academy of Science of Belarus; Joint Institute of Solid State and Semiconductor Physics, National Academy of Science of Belarus

InN has attracted great interest as a promising material for THz emission, high frequency electronics and various sensors. Although high quality InN layers can be grown by molecular beam epitaxy, this material is not commercialized. Hydride Vapor Phase Epitaxy (HVPE) is known to produce high quality nitride materials with high throughput. Results on HVPE of InN are limited and the quality of reported material is low. We report the first demonstration and properties of high quality HVPE InN. Layers are grown on GaN/sapphire. The (00.2) XRD rocking curves (RC) had the FWHM of about 510 arc sec, being the narrowest RCs ever reported for HVPE InN. Photoluminescence showed edge emission around 0.8 eV. Hall measured free electron concentration is in the range of $10^8$-$10^9$ cm$^{-2}$ and electron mobility is ~200 cm$^2$/V s. For the first time high quality HVPE InN is grown opening new ways for this material.

MIS Structures with Low Interface States Density: SeC03/GaN, MgO/GaN, and MgScO/GaN: Alexander Polyakov; Nikolai Smirnov; Brent Gila; Mark Hlad; Andrew Gerger; Cammy Abernathy; LarsVoss; Stephen Pearton; Institute of Rare Metals; University of Florida

Interface trap densities were measured in SeC03/n-GaN, MgO/n-GaN, and MgScO/n-GaN MIS structures using conductance and DLTS methods. Both techniques give for energies deeper than 0.3 eV from the conduction band edge the interface trap density on the order of $10^{12}$ cm$^{-2}$V$^{-1}$. DLTS measurements show that the interface trap density has a peak near 0.6-0.7 eV from the bottom of conduction band. The interface trap density measured both by conductance and DLTS methods increases in the order SeC03, MgO, MgScO which most likely reflects the improved lattice match of corresponding oxides with GaN. For MgScO/n-GaN structures we also observed generation of additional interface traps by the application of high positive bias. The effect could be reversed after a high negative bias was applied while annealing the sample.

New Results on HVPE Growth of AlN, GaN, InN and Their Alloys: Alexander Usikov; Vitaliy Soukhoveev; Liza Shapovalova; Alexander Syrkin; Oleg Kovalenkova; Anna Volkova; Vladimir Sizov; Vladimir Ivantsov; Vladimir Dmitriev; TDI, Inc.

We describe new results on HVPE growth of group III nitride layers and heterostructures including AlN, GaN, InN and their alloys. AlN, GaN, and AlGaN were grown on sapphire and SiC. Stress control HVPE was explored to grow crack-free 4-inch AlN(20 μm)/SiC structures with zero bow and improved crystal quality and surface morphology. GaN growth rate ranged from 1 to 1,000 microns per hour. Low growth rates resulted in HVPE-first GaN/AlGaN quantum wells. P-type as-grown GaN<$<$Mg$>$ layers with hole concentration in the E18 cm$^{-3}$ range were obtained. P-type GaN layers and AlGaN/GaN structures with two dimensional hole gas were grown using Zn doping. InGaN layers from 0.002 to 0.02 microns thick with InN content from 0 to 100 mole % were grown on GaN/sapphire substrates. Blue and green all-HVPE LEDs were made based on InGaN/InGaN multi-layered structures, for the first time. New directions of HVPE development will be discussed.

Pulsed Layer Growth of AlInGaN Nanostructures: Michael Jetter; Peter Michler; Universiteit Stuttgart, Institut fuer Halbleiteroptik und Funktionelle Grenzflaechen

In this contribution we report on the growth and characterization of AlGaN nanostructures fabricated with a pulsed layer growth method with metal-organic vapour-phase epitaxy (MOVPE). The amount of material was varied, resulting in AlGaN layer thicknesses between 1.5 nm and 6 nm, respectively. We have analyzed the material properties by x-ray diffraction (XRD) as well as photoluminescence (PL) spectroscopy. The observed XRD-spectra and the PL intensity show us the high quality of the deposited material. From the analysis of the PL spectra we have found an energetic shift of the resonance lines from 2.65 eV to 3.33 eV with decreasing well thickness. With power-, temperature-dependent and time-resolved PL experiments we have monitored the energetic levels and the carrier dynamics inside the structures to reveal the character of the observed emission. Additionally Cr-shadow masks were processed on the sample to get insight into the local material distribution, respectively luminescence behaviour.

Room Temperature Epitaxial Growth of GaN on β-Ga2O3(100) Substrates: Jitsuo Ohta; Atsushi Kobayashi; Satoshi Kawano; Hiroshi Fujikoka; Shigeo Ohira; University of Tokyo; 'Nippon Light Metal Company

We have investigated characteristics of GaN films grown on β-Ga2O3(100) substrates at room temperature (RT) by pulsed laser deposition (PLD). Growth of GaN films at 750 °C has resulted in the formation of polycrystalline materials with both zincblende and wurzite phases, which is probably due to the intermixing reactions at the GaN/β-Ga2O3 hetero-interface. On the other hand, pure wurzite GaN films with high crystallinity grow epitaxially at RT with an in-plane epitaxial relationship of [11-02]Ga2O3/[100] GaN. This success can be attributed to the suppression of the interface reactions by the reduction in the growth temperature. We have also found that the heterointerfaces prepared at RT are thermally quite stable and we can grow GaN films at 750 °C using the RT GaN films as buffer layers. These results indicate that RT-growth technique enables us to improve crystalline quality of GaN on Ga2O3 and is quite promising for fabrication of future UV LEDs.

Strains and Stresses in Nitride Growth: On the Limits of Stoney’s Equation: Reiner Cloi; Armin Dadgar; Fabian Schulze; Alois Krost; Otto V. Guericke University

In last years in-situ curvature measurements have become a standard tool for monitoring strains and stresses during epitaxy. This technique is based on the measurement of the substrate curvature k usually in the center of the wafer. The method always requires an equation, which correlates the curvature with the incompatibility strain arising from lattice mismatch, thermal mismatch, growth-induced mismatch etc. Usually, the data are interpreted in terms of the classical Stoney equation which is, however, limited to thin films and homogeneous stresses. We have developed general expressions for the curvature-incompatibility strain relationship in the case of large bending and arbitrary thickness ratios between film and substrate, which can be solved to a large extent analytically in the case of cylindrical symmetry. It is shown that the limits of Stoney’s formula are easily reached in the case of, e.g., GaN on Si, large diameter wafers, thick layers, or temperature gradients.

Structural Properties of AlN Grown on Sapphire at Plasma Self-Heating Condition Using Ultrahigh-Vacuum Unbalanced Magnetron Sputtering: Huichan Seo; Ivan Petrov; Kyekyoon Kim; University of Illinois at Urbana-Champaign

AlN films were grown on sapphire substrate by ultrahigh-vacuum unbalanced magnetron sputtering in N2 discharges at growth temperature as low as 94°C. The structural properties with different substrate bias and growth pressure were investigated by atomic force microscopy and X-ray diffraction measurements. At 20 mTorr there were AlN (002) and (10-11) peaks and with increasing substrate bias the X-ray peak intensity of AlN (002) increased with enhanced film quality and at higher bias (Vs> 25 V) the film began to degrade. With decreasing growth pressure AlN (10-11) peak disappeared and the crystallinity of AlN was improved with relaxed single AlN crystal. The measured lattice parameter a was 0.49753 nm which was 0.084 % smaller than that of bulk. The epitaxial relationship of single crystal
A thin nitride film was found by pole figure and cross sectional transmission electron microscopy: (001)AlN / (001) S, [1-10] AIN / [1-10] S.

The Study of Interface Properties of III-Nitrides on Lithium Niobate for Multifunctional Optoelectronic-Acoustic-Electronic Applications: Kyong-Keun Lee; Gun Namkoong; William Doohil; Maria Losurdo; Giovanni Bruno; Hyung Koun Cho; Georgia Institute of Technology; Old Dominion University; Institute of Inorganic Methodology and of Plasmas IMIP-CNR; Sung Kyun Kwan University

This work presents a solution to the problem of ferroelectric repolarization on congruent lithium-niobate (CLN) for use in the epitaxy of III-Nitride multifunctional optoelectronic-acoustic-electronic applications. By lowering the annealing temperature, repolarization is eliminated at the expense of surface smoothness. The annealed CLN substrates show a surface roughness from 0.2 to 5.5 nm with no ferroelectric repolarization below 1000°C. Furthermore, according to X-ray diffraction, GaN films grown on the annealed CLN below 1000°C have no significant crystalllographic differences from those grown on stoichiometric LN – a more expensive and rare substrate. Also according to XRD, the hexagonal structure of GaN is rotated 30 degree relative to the LN hexagonal structure, as expected, but the GaN on LN is epitaxial. However, cross-sectional TEM images of the GaN and substrate interface shows an approximately 18 nm thick interface region with stacking faults and mixed phases of cubic and hexagonal GaN.

Suppression of Interdiffusion at the Heterointerface of AlN/ZnO: In Ho Im; Seog-Woo Lee; Jin-Suh Park; Tsutomo Minegishi; Seung-Hwan Park; Takashi Hanada; Ji-Ho Chang; Meung-wohan Cho; Takafumi Yao; Institute for Materials Research, Center for Interdisciplinary Research, Tohoku University; Major of Semiconductor Physics, Korea Maritime University

Since ZnO can be both conductive and resistive, interface layers which act as a diffusion barrier in between III-nitrides and ZnO would make ZnO more attracting as a substrate for III-nitride epitaxy. This paper reports that AlN does act as a superior interface barrier for III-nitride growth. We compare two nitride layers as a diffusion barrier: GaN and AlN. Although GaN layers are grown at low temperatures below 600°C, serious interdiffusion at the GaN/ZnO interface is observed with the diffusion length of Ga into ZnO being 1 μm. On the contrary, AlN layers deposited even at 1000°C show only slight diffusion with a diffusion length of Al into ZnO being 100 nm. The superior properties of AlN as a diffusion barrier arise from the strong bonding energy of AlN. We compare structural, electrical, and optical properties of free-standing GaN layers grown on low-temperature GaN buffer and AlN buffer.

The Growth of Bulk Gallium Nitride (GaN) Using Hydride Vapor Phase Epitaxy (HVPE): Moon Sung Lee; Samsung Advanced Institute of Technology(SAIT)

Because of the lack of suitable nitride substrates, films of GaN and related nitride compounds have been commonly grown on sapphire substrate. The use of this foreign substrate causes many problems in growing GaN films such as numerous threading dislocations, stress and bowing. It also complicates the processing steps such as formation of laser cavity and electrical contact and causes the degradation of the device. Therefore, it is desirable to employ the homoepitaxial growth on the GaN substrate. In this report, we report on the origin of defect and characteristics of bulk GaN grown by HVPE.

The Passivated Pendeo Structure for the Efficient Self-Separation of the Freestanding GaN: Po Chun Lai; Hsin Hsieng Huang; Jenq Dar Tsay; Tung Wei Chi; Yih Der Guo; Ruey Chyn Yeh; Institute of Technology Research Institute (ITRI)

A self-separated freestanding Gallium Nitride grown by the Hydride Vapor Phase Epitaxy (HVPE) is obtained using the SiOx passivated straight Pendeo (Air Bridge). The GaN can be fully lifted off from the Air Bridge structure, but GaN bulk creaked into several pieces during cooling down process. However, no creaks were found on the whole 2 inch sapphire substrate. For the purpose of comparison, the conventional Pendeo structure was also carried out under identical parameters. The self-separation was not efficiently presented on the Pendeo structure. In addition to this, lots of cracks appeared on the sapphire surface and the GaN, respectively. This could be induced by the thermal expansion coefficient mismatch between the GaN layer and the sapphire. Furthermore, the GaN growing on the sapphire should be another cause of cracks formation. It shows the Air Bridge structure can sufficiently enhance the self-separation of freestanding GaN.

Technical Program

Ab-Initio Study of Compositional Anti-Correlation of In and N in InGaAsN Alloys: Hasan Abe-Farsakh; Joerg Neugebauer; Martin Albrecht; Max-Planck-Institut fuer Eisenforschung; Institut fuer Kristallzuechtung

InGaAsN quantum wells have attracted considerable interest as potential candidates for manufacturing infrared laser diodes. Major challenges in epitaxially growing these quaternary alloys with high structural and compositional perfection are compositional fluctuations and a tendency of 3D growth at higher temperatures. A prominent example is the recently experimentally observed but hitherto not understood anti-correlation between In and N which largely affects the optical properties of these alloys. In order to identify/understand the underlying mechanisms we have employed density functional theory to analyze the thermodynamic and kinetic processes of In-N incorporation during growth. Based on these results we show that the In-N anti-correlation results from an intricate interplay between strain and chemical energy and is driven by surface kinetics. This detailed insight allows us to discuss possible strategies how to control the In-N correlation.

Analysis of Strain and Validity of Vegard’s Law in the AlGaN Thin Films: Albert Davydov; William Boettiger; Alexander Shapiro; Norm Sanford; Vitaly Soukhoveev; Vladimir Dmitriev; Stacia Keller; National Institute of Standards and Technology; TDI, Inc; University of California, Santa Barbara

Compositional band-gap bowing in AlGaN, N alloys is a well-established effect, which needs to be taken into account for device engineering. Evaluation of the E_g vs. x bowing parameters requires accurate determination of alloy composition, which is often inferred from postulated Vegard’s law for AlGaN, N lattice parameters vs. x. This paper examines validity of Vegard’s law in the AlGaN system by exploring relationship between measured (stressed), calculated (stress-free) wurtzite lattice parameters and independently determined composition x in HVPE and MOCVD grown AlGaN,N/c-sapphire films. XRD, EDS and RBS measurements combined with strain-stress modeling revealed positive deviation from Vegard’s law in this system with evident bowing remaining even for the stress-free a_0 and c_0 lattice parameters. Validated a_0(x) and c_0(x) dependencies can further be applied for evaluation of x in AlGaN,N films with unknown composition. Possible origin of deviation from Vegard’s law and its relation to thermal properties of AlGaN,N alloys is discussed.

Band Gap of Miscible InGaAlBN for Use in Optical Communications Systems: Takeshi Kimura; Takashi Matsuoka; Tohoku University

The relationship between the lattice constant and energy-band gap for the InGaAlBN system was calculated for the miscible regions using the strictly regular solution approximation. Near the InN-rich region, the InGaAlBN had the largest band gap of 3.4 eV, near the line from GaN to AlN, as calculated using the strictly regular solution approximation. Near the InN-rich region, the InGaAlBN had the same band-gap difference, ΔE_g, between the active and cladding layers at optical communication wavelengths as InGaAsP under the condition of lattice-matching between layers. When a strained layer, which is useful for high-performance devices, is used as an active layer in the infrared region, the ΔE_g of InGaAlBN is larger than those of InGaAsP and InGaAIN. Moreover, the InGaAlBN system enables the fabrication of optical devices under the lattice-matching condition in a much wider range, such as from green to ultraviolet, than InGaAIN.
Technical Program

**Binding Energies of Hydrogenic Impurity States in GaN/AlGaN Triangular Quantum Well Structure:** Zhen Chen; University of California, Santa Barbara

The ground-state binding energies of a hydrogenic impurity in a triangular quantum well structure are calculated using a variational approach. This model is valid for the common heterostructures, especially materials with a large polarization field, such as GaN/AlGaN. The binding energies are calculated as a function of the slope of the triangular potential for a given position of impurity, and as a function of the position of the impurity for a given electric field.

**Current Spreading, Heat Transfer, and Light Extraction in a Multi-Pixel LED Array:** Maxim Bogdanov; Kirill Bulashevich; Igor Evtstratov; Sergey Karpov; Soft-Impact, Ltd.; Semiconductor Technology Research, Inc.

We report on coupled 3D simulation of the current spreading, heat transfer, and light extraction in a conventional square light-emitting diode (LED) and a multi-pixel LED array recently suggested to improve the high-current device performance. The square LED is found to suffer from a considerable overheating that results in the emission power rollover at high currents. In contrast, the thermal effects are suppressed in a multi-pixel LED even at higher currents, providing very uniform distribution of the wavelength and light emission intensity among the individual pixels. The modeling reproduced quantitatively well the observed dramatic difference in the LED series re-sistance due to the die design, the current dependence of the output power, and other operational features of the LEDs. The 3D ray-tracing is used to estimate the light ex-traction efficiency through a semitransparent p-electrode and to identify the channels of optical losses in the dice.

**Density Functional Theory Calculations of the Strain Effects on Binding Energies and Adatom Diffusion for GaN (0001) Surfaces:** James Grandusky; Vihbu Jindal; Neeraj Tripathi; Mihir Tungare; James Raynolds; Fatemeh Shahedipour-Sandvik; University at Albany, SUNY

Density functional theory calculations were carried out to study the binding energies and diffusion barriers for adatoms on GaN. The binding energies and diffusion barriers were calculated for Ga and N adatoms on both Ga terminated and N terminated (0001) surfaces, subjected to a hydrostatic compressive and tensile strain in the range of 0 to 5%. A complete understanding of the changes in adatom binding and diffusion under differing growth conditions was obtained. For example, the diffusion barrier of a Ga adatom is maximum for a 1% compressive strain and decreases rapidly at higher strains whereas the diffusion barrier for a N adatom is lowest at a 1% tensile strain and increases as the strain increases on a N terminated surface. These changes can explain differences in optimal growth conditions on bulk III-Nitride substrates as opposed to on III-Nitride template layers on foreign substrates.

**DFT Study of Edge Dislocations and Tilt Grain Boundaries in GaN and AlN:** Sébastien Petit; Imad Belabbes; Huaping Lei; Jun Chen; Pierre Ruterana; Gerard Nouet; University of Caen Basse-Normandie, Normandy; Structure of the Interfaces and Functionality of the Thin Layers and Shanghai Institute of Microsystem and Information Technology, State Key Laboratory of Functional Materials for Informatics; Institut Universitaire Technologique d’Alençon, Laboratoire de Recherche sur les propriétés des Matériaux Nouveaux

Layers of III-V nitride semiconductors grown on various substrates as sapphire or silicon carbide may contain huge densities of threading dislocations. In wurzite GaN, the majority of these dislocations are edge with b=1/3<11-20>. The coincidence <0001> tilt grain boundaries are also observed in nitride layers, but in smaller concentration. These dislocations and boundaries can all be described in terms of a combination of the three cores of the edge dislocation: the 5/7-, 8- and 4-atoms rings. On the basis of the Density Functional Theory (DFT) implemented in the AIMPRO code, we have made a comparative analysis of the structural and electronic properties of edge dislocations and tilt grain boundaries with various coincidence orientations (sigma = 7, 13, 19 and 37) in the two nitride Semiconductors GaN and AlN.

**Electronic Basic Transition of Zincblende In(x)Ga(1-x)N/In(y)Ga(1-y)N Quantum Wells:** Heriberto Hernandez Cocoltezi; Jesus Madrigal-Melchor; Stoyan Jelev-Vlave; I. Rodriguez-Vargas; David Armando ContrerasSolores; Benemérita Universidad Autónoma de Puebla; Universidad Autónoma de Zacatecas, Unidad Académica de Física

Generally, the principal part of LED and laser devices made of nitrides, is an InGaN quantum well. In this work, for that type of wells in cubic phase, we calculate theoretically the fundamental transition from the first energy level of holes to the first energy level of electrons, 1h-1e. For calculations, we use several values for the band offset at the In(x)Ga(1-x)N/In(y)Ga(1-y)N interface and well width, and various concentrations of In. We use the Surface Green Function Matching method and the first neighbor tight binding approximation with a sp3* basis, taking into account the spin-orbit interaction. We use tight binding parameters that give a value of 0.65 eV for the InN band gap. For the InGaN alloy we use the virtual crystal approximation. We incorporate the biaxial stress in the well, due to the different values of lattice constants between the well and the barriers.Work partially supported by VIEP-BUAP.

**Electronic Spectral Densities and Spectral Line Profiles in Quantum Dots:** Karel Kral; Academy Science of Czech Republic, Institute of Physics

Spectral line profiles of luminescence transitions in individual quantum dots have been studied in recent years and shown to be quite different from the simple form the Lorentzian line shape. Here we turn the attention to earlier calculations and measurements and compare them with the electronic spectral line profiles in individual quantum dots calculated under the assumption of quantum dot electrons interacting with the longitudinal optical phonons only. The calculated luminescence spectral line profiles will be presented and compared to the calculated electronic spectral densities which develop in the course of relaxation processes or other kinetic processes in quantum dots. The spectral densities will be numerically evaluated in the self-consistent Born (SCB) approximation to the electronic self energy. We will show the agreement of the calculated spectral line profile of the lowest energy excited state with experimental data and with other calculations.

**Filling the Green Gap: A First-Principles Study of the LiMg,N/Zn,N Alloy System:** Aron Walsh; Su-Huai Wei; National Renewable Energy Laboratory

The lack of an efficient emitter in the 500-600nm range is severely limiting the widespread adoption of light emitting diodes for indoor lighting applications. The degradation in performance of the current In and Ga nitride alloys in this range is largely due to their lattice mismatch and associated phase instabilities. We propose and investigate the electronic structure of an alternative system, which has the potential to fill this green gap. The small lattice mismatch between LiMgN and LiZnN along with their electronic bandgaps spanning the visible range, make them in principle, ideal candidates.

**First Principles Model of Bandgap Lowering in Dilute III-V-Nitrides: Beyond Band Anticrossing:** Vincenzo Lordi; James Harris; Stanford University

The remarkable property of III-V-N compounds is the sharp band gap lowering upon incorporation of small amounts of nitrogen. A popular model based on band anticrossing (BAC) is often used to explain the effect. We present a more comprehensive physical model based on *ab initio* calculations to explain the phenomenon over a broader applicable composition range. We find that BAC is a good descriptor of the very low concentration limit, but that a crossover to a N cluster-dominated description occurs at higher concentrations. The N clusters create energy states within the host band gap near the CBM, which hybridize into a “N band.” The result is a band gap lowering that is steeper at low concentrations and begins to flatten as the interaction between N atoms increases at higher concentrations. A portion of this work was performed under the auspices of the U.S. DoE at UC/LLNL under contract no. W-7405-Eng-48.
Ga-Frenkel Pairs in GaN Investigated via g-Tensor Calculations: Uwe Gerstmann1; Francesco Mauri1; Université Pierre et Marie Curie, Paris

In GaN, an exceptionally important role is played by Ga-interstitials being mobile at room temperature. Despite rather large formation energy, they have been observed in irradiated wurtzite-GaN: two similar ODEPR-signals L5/L6 have been identified as interstitial Ga+. The ODEPR-signals L5/L6 have been identified as interstitial Ga+ in two different lattice configurations. However, judging from experimental data and total energy calculations alone, the exact microscopic configuration remained unclear. In this work, the situation is elucidated by calculating the complete set of EPR parameters, hyperfine splittings as well as g-tensors, for reasonable defect models using a gauge-including projector augmented plane wave (GI-PAW) approach. We first show that the usual inequivalent interstitial sites, the O-site and T-site, provide almost identical hyperfine splittings. The isotropy of the g-tensor turns out to be a much more rigorous criterion, ending up in a model with near and distant frenkel pairs of a Ga-interstitial at the O-site and a distant Ga-vacancy as a rather small modification.

Lasing Threshold of 280 nm AlGaN Lasers under High Threshold Gain Conditions: Weng Chow1; Mary Crawford1; Andrew Allerman1; Michael Kneissl2; 1Sandia National Laboratories; 2Technical University of Berlin

This paper analyses the threshold current density versus threshold gain relationship for AlGaN lasers operating in the deep UV. The calculations are based on the semiconductor Bloch equations, where bandstructure, internal electric field and many-body effects are treated rigorously. The results show a strong dependence of threshold current density on threshold gain, lasing polarization, barrier Al concentration and quantum well (QW) width. The QW configurations, i.e. QW widths and barrier compositions, giving the lowest threshold current densities are distinctly different for low and high threshold gains (e.g. GGth = 40cm-1 and 120cm-1, respectively). We also found that laser emission switches between TE and TM mode depending on the operating conditions and QW configuration. These differences are a consequence of the intricate interactions among band structure, internal field and many-body interaction.

Magnetic Interactions in GaN: A Comparative Investigation of Cr, Mn, Fe, and Co Impurities: Lucy Assali1; Wanda Machado2; Joao Justo2; 1Universidade de Sao Paulo, Instituto de Fisica; 2Universidade de Sao Paulo, Escola Politecnica

Interest in magnetic semiconductors has grown considerably, as a result of a theoretical prediction that manganese doped III-V semiconductors could retain magnetic properties up to room temperature. Those properties open a wide range of potential applications, such as spintronic devices. In this work, we present an ab initio investigation on the structural, electronic, and magnetic properties of isolated 3d transition metal impurities (Cr, Mn, Fe, and Co) in GaN. We considered the impurities in the substitutional cation sites, and the material in both cubic and hexagonal phases. Our calculations were performed within the all-electron spin-polarized full-potential linearized augmented plane wave methodology. The calculations provided the stable configurations, symmetries, spin states, formation and transition energies, and magnetic moments of those impurities in GaN. A comparative study on all those impurities allowed to build a microscopic model for the chemical trends of 3d transition metals in III-nitrides semiconductors.

Ordering, Phase-Separation and Suppression of Phase Separation in InN-GaN Alloys: Zhe Liu1; Giancarlo Tramarchi3; Alex Zunger1; 1National Renewable Energy Laboratory

Large atomic-size mismatch (over 10%) between InN and GaN has long been known to lead to phase separation into InN-rich and GaN-rich phases at their own equilibrium lattice constants (inherent phase separation). Such inhomogeneous mixtures can severely limit many technological applications that rely on carrier transport. We show theoretically that this size-mismatched alloy has specific coherent, three-dimensional tetrahedral networks with much lower energies than both the equivalent random alloys and coherently separated constituents (i.e., both constituents have the same lattice constant at the interface). Such homogeneous structures are predicted to order at low temperature, and are characterized by alternate atomic bi-layers along the (201) crystallographic direction, akin to the (AC)2/(BC)2 (201) chalcopyrite (CH) crystal structure. The prediction of bulk stable ordered structure provides a mechanism to understand ordered structures observed in experiments of bulk III-V zincblende semiconductor alloys.

Polarization Fields in Wurtzite Strained Layers and Heterostructures Grown on (hkl)- Oriented Substrates: Bernard Gil1; Pierre Bigenwald2; 1National Center of Scientific Research; 2Universite Blaise Pascal Clermont Ferrand 2

This work analyses the threshold current density versus threshold gain and Co) in GaN. We considered the impurities in the substitutional cation. In this work, the situation is elucidated by calculating the complete set of EPR parameters, hyperfine splittings as well as g-tensors, for reasonable defect models using a gauge-including projector augmented plane wave (GI-PAW) approach. We first show that the usual inequivalent interstitial sites, the O-site and T-site, provide almost identical hyperfine splittings. The isotropy of the g-tensor turns out to be a much more rigorous criterion, ending up in a model with near and distant frenkel pairs of a Ga-interstitial at the O-site and a distant Ga-vacancy as a rather small modification.

Quantum-Confinement Effect and Intersubband Transitions in Zinc Blend AlGaNAIN Quantum Cubes: Shih-Wei Feng1; Kuei-Hsien Chen1; 1National University of Kaohsiung; 2Academia Sinica, Institute of Atomic and Molecular Sciences

In this work, by using a series expansion model to calculate the band structures of a AlGaNAIN quantum cube, we theoretically study the quantum-confinement effects and its impacts on the band structures and intersubband (ISB) transitions in ZB AlGaN quantumdots. Without spontaneous and piezoelectric polarization fields, the quantum confinement effect and size-tunable emission properties of ZB AlGaNAIN quantum cubes can be completely explored. Simulations results show the important factors of the composition, cluster size, quantum confined potential, effective mass, and strain in determining the optical properties and band structures of such a semiconductor compound. Meanwhile, calculation results reveal that the cube sizes as well as composition contrast must be larger such that ISB transitions between electron eigenstates can be used for telecommunication devices. These simulation results of quantum-confinement effects, size-tunable emission properties, ISB transitions, and ISB absorptions can provide significant information for the devices designs and fabrications.

Structural Analysis of In-Rich Clusters in InGaN Quantum Wells: Huaping Lei1; Xunya Jiang2; Jun Chen3; Sébastien Petit4; Pierre Ruterana1; Gerard Nouet1; 1University of Caen Basse-Normandie, Structure of the Interfaces and Functionality of the Thin Layers and Shanghai Institute of Microsystem and Information Technology, State Key Laboratory of Functional Materials for Informatics; 2State Key Laboratory of Functional Materials for Informatics, Shanghai Institute of Microsystem and Information Technology; 3Institut Universitaire Technologique d’Alençon, Laboratoire de Recherche sur les propriétés des Matériaux Nouveaux; 4University of Caen Basse-Normandie, Structure of the Interfaces and Functionality of the Thin Layers

For the GaNInGaN quantum wells, the mechanisms of light emission are still controversial: the formation of clusters due to the indium segregation should result in the localisation of the carriers and be a centre for radiative recombination. Simulation of these heterostructures needs the calculation of the atomic structure and strain energy. The size of the clusters can be large, the cell must contain tens of thousand of atoms and only empirical potentials are suitable. The choice of the Stillinger-Weber potential is justified by our previous analysis of extended defects in GaN. A set of parameters for In and N atoms has been evaluated in order to reproduce the crystallographic parameters, bulk modulus and elastic constants of InN. Subsequently, the combination of the SW parameters for Ga, In and N atoms allows us the calculation of the atomic structure and properties of InGaN alloys with different In concentration.

Structural and Dynamical Properties of AlInGaN Alloys: H. W. Leite Alves1; J. L. A. Alves1; Luisa Scalfer2; 1Universidade Federal de São João del Rei, Departamento de Ciências Naturais; 2University of Sao Paulo, Physics Institute

In this work, we have calculated ab initio, by using the Density Functional Theory within the Local Density Approximation, gradient conjugated
The Surface Magnetoplasmon Polariton in GaN (Doped)-AlN (Undoped) Semiconductor Superlattice: Saber Farjami Shayesteh; ’University of Guilan

The effective medium dielectric tensor of a superlattice is employed to describe doped-undoped GaN-AlN semiconductor superlattic in an external magneto-static field. According to direction of magnetic field, there configuration perpendicular, Faraday and Voigt are defined. The properties of surface polariton have been consider in detail for the perpendicular (applied magnetic field perpendicular to interface) and Faraday configuration (magnetic field parallel to interface and along with propagation vector). The dispersion relation of surface magnetoplasmon polariton is calculated for GaN (doped)-AlN (undoped) multi quantum wells. Numerical exploration shows frequency of the generalized surface wave increases as \( \omega_c \) increases. Also, it is seen that as the field value increases the frequency of surface mode increases. In Addition to, calculated dispersion curve shows the surface mode propagation is reciprocal, \( \omega(k) = \omega(-k) \), for both perpendicular and Faraday configurations. Furthermore, the dispersion curve varies with the volume fraction of the doped constituent.
Using p-Type InAlGaN Layers: Recent Progress in AllInGaN Based Deep Ultraviolet Light Emitting Diodes:ASTEFränkel; 1University of Darmstadt Several groups have reported on deep ultraviolet light emitting diodes (LEDs) for applications in air-water and food purification. The first generation devices, with emission from 340 nm to 280 nm typically have cw-powers as high as 1 mW (at 20 mA) and wall-plug efficiencies of about 1%. Their average lifetimes at 20 mA are only about 500 to 1000 hours. Due to increased number of extended defects, these performance numbers drop with decreasing emission wavelength. Currently several groups including ours are exploring ways to produce more robust devices with higher emission efficiencies. In this paper we will review the issues limiting the first generation devices’ performance followed by new AlGaN and InGaN lateral epitaxy approaches leading to second generation deep UV LEDs with significantly improved lifetime-efficiency values. Finally we will discuss the potential of fabricating non-polar deep UV LEDs.

9:30 AM
J2, 340nm-Band High-Power (>7mW) InAlGaN Quantum Well UV-LED Using p-Type InAlGaN Layers: Sachie Fujikawa1; Takayoshi Takano2; Yukihiro Kondo2; Hideki Hirayama2; ‘RIKEN’; Matsuushita Electric Works, Ltd.

In order to achieve high-efficiency ultraviolet (UV) light-emitting diodes (LEDs), p-type layers with sufficient hole concentration is quite important to suppress the electron overflow. We introduced Mg-doped InAlGaN layers for p-type layers of the UV-LEDs for the purpose of obtaining higher hole concentration, and achieved high power CW operations (>7 mW) of the UV-LEDs. 340nm-band InAlGaN-based multi-quantum-well (MQWs) UV-LEDs with Mg-doped InAlGaN electron-blocking layer and p-type layers were grown on the sapphire substrates by metal-organic chemical vapor deposition (MOCVD). The output power of UV-LED with p-InAlGaN layers (6.6mW) was approximately 4.7 times larger than that with p-AlGaN layers (1.4mW). Maximum output power and the external quantum efficiency (EQE) of the quaternary InAlGaN based UV-LED were 7.1mW and 0.9%, respectively, at emission wavelength of 346nm under room temperature (RT) CW operation. From these results, p-InAlGaN is shown to be quite useful for the realization of high-efficiency UV-LEDs of high-efficiency UV-LEDs.

9:45 AM
J3, AlGaN Based Deep UV LEDs with Emission at 230-270 nm: Jianping Zhang1; Yuri Bilenko1; Xuhong Hu1; A. Lunev1; A. Sattu1; J. Deng1; M. Shatalov1; W. Sun1; J. Yang1; R. Gaska1; ‘Sensor Electronic Technology’

We report on development of AlGaN deep UV LED with emission wavelength from 230 nm to 270 nm. The LED structures were grown over (001) sapphire substrates using proprietary MEMOCVD process. LEDs showed strong emissions at as short as 223 nm. The voltages at 20 mA ranged from 8 V to 6 V with the series resistances between 35 Ω and 20 Ω for 247 nm and 270 nm LEDs, respectively. At 20 mA the output power of 50 µW and 1.34 mW were measured at 247 nm and 269 nm, respectively. The current power for 269 nm LED reached 3.25 mW at 50 mA. Maximum powers of 9 mW at 1.4 A for 247 nm and 50 mW at 2 A for 269 nm emitting LEDs were measured under pulse excitation.

10:00 AM
J4, Nitride-Based Microcavities with Quantum Wells and Quantum Dots as Active Region: Carsten Kruse1; Stephan Figgel2; Heiko Dartsch2; Timo Aschenbrenner1; Christian Tessarek1; Henning Lohmeyer1; Kathrin Sebald1; Juergen Gutowski1; Detlef Hommel1; ‘University of Bremen’

We realized monolithic GaN/Al0.4Ga0.6N-based microcavities (MCs) with Q-values around 300 grown by MOVPE and plasma-assisted MBE. These structures are fully strained as determined by HRXRD and of good structural quality according to SEM pictures. We also fabricated hybrid microcavities having a dielectric SiO2/TiO2 layer stack as the top DBR in order to have a higher flexibility for integrating temperature-sensitive active regions like InGaN-QD sheets into the MCs. Two main applications are in focus: VCSELs with either QW and QD stacks as active region for lasing applications or MCs with single sheets of QDs with a comparatively low density in the range of 1010 – 1011 cm2 for use as a single-photon emitter. We will discuss growth related issues like strain engineering using suitable AlGaN template layers and the two-step growth of InGaN-QDs. Furthermore, optical properties of planar MCs and microcavities will be addressed.

Technical Program
Technical Program

9:15 AM
K2, Enhancement-Mode AlGaN/GaN HEMTs with Thin InGaN Cap Layer: Masafumi Ito; Shigeru Kishimoto; Fumihiko Nakamura; Takashi Mizutani; Nagoya University, Department of Quantum Engineering; Venture Business Laboratory; POWDEC K.K.

AlGaN/GaN HEMTs receive much attention for high-power and high-frequency applications. In order to apply them to the high-power switching systems, normally-off HEMTs are indispensable. In this report, we propose to introduce a thin InGaN cap layer on a conventional AlGaN/GaN HEMT structure to implement the normally-off HEMTs. Polarization field in the InGaN cap layer is expected to raise the conduction band of the AlGaN/GaN interface leading to a threshold voltage shift to positive direction. It is possible to decrease the parasitic source resistance by removing the InGaN cap layer at the access region. Fabricated HEMT with 5 nm thick In0.2Ga0.8N cap layer showed normally-off operation with a threshold voltage of 0.3 V and a maximum transconductance (gmmax) of 145 mS/mm. The gmmax was comparable with the normally-on HEMT without the InGaN cap layer. These results confirm the validity of introducing an In0.2Ga0.8N cap layer to implement the normally-off HEMTs.

9:30 AM
K3, Growth and Characterization of AlInN/GaN Field Effect Transistors: Jean-François Carlin; Farid Medjoubi; Marcus Gonschorsek; Eric Feltin; Marcel Py; Christophe Gaquiere; Nicolas Grandjean; Erhard Kohl; EPEF; University of Ulm (EBS); IEEM/TIGER

Lattice-matched Al0.83In0.17N/GaN high electron mobility transistors (HEMTs) are grown by metalorganic vapor phase epitaxy. A thin AlN interlayer is inserted at the interface in order to reduce the alloy scattering. Room-temperature mobilities of 1200 cm2/Vs are then been obtained with n5 as high as 2.6×1013 cm-2. Standard structures (15um barrier, lattice-matched AlInN/GaN) typically exhibit 2 A/mm drain current density. Growth optimization on various substrates (sapphire, Silicon and SiC) and characterization of AllnN materials are discussed. Transistors having a reduced barrier thickness as low as 5 nm still provide high output current density and transconductance about 500 mS/mm. A good threshold voltage scaling with the AlInN barrier thickness reduction is observed. The high potential of the AlInN/GaN system is confirmed on HEMT devices. DC measurements demonstrate an open channel drain current density of 2.6 A/mm on HEMTs with 50×0.25 um2 gate geometry.

9:45 AM
K4, GaN HEMT Thermal Behavior and Implications for Reliability Testing and Analysis: Daniel Green; Bharath Vembu; David Hepper; Shawn Gibb; Daniel Jin; Rama Vetury; Jeffrey Shealy; Thomas Beechem; Samuel Graham; RFMD Infrastructure Product Group, Inc.; Georgia Institute of Technology

GaN HEMT reliability evaluation in a typical Arrhenius manner requires establishing peak junction temperature for a particular stress condition. Several new techniques have yielded promising results toward establishing peak temperature for these devices in combination with a detailed physical modeling, particularly micro-Raman imaging. This paper compares results from finite element modeling to measurements by infrared imaging and micro-Raman imaging. The limitations of IR imaging were confirmed similar to earlier reports. Two techniques for establishing temperature from micro-Raman measurements were used to reveal excellent correlation to the model, and also provide insight into the relationship between temperature and structural change in the device. Temperature data is reported for base plate temperature from 85°C to 140°C for practical GaN HEMT devices. Implications of the measurements for GaN HEMT reliability stress testing and analysis will be discussed.

10:09 AM
K5, Nanosecond Thermal Transients in Pulsed High-Power AlGaN/GaN Devices Using Time-Resolved Micro-Raman Thermography: Gernot Riedel; J. Pomeroy; M. Kuball; M. Uren; T. Martin; University of Bristol; QinetiQ Ltd

Microwave power transistors are typically operated pulsed for use in communications and radar applications, resulting in fast thermal transients due to self-heating and thermal diffusion. Since self-heating degrades performance and reliability, it is important to monitor the temporal evolution of device temperature on short time-scales. Transient thermal simulations, commonly used for this purpose, are strongly affected by uncertainties in input parameters in particular within the initial 50-200ns of the temperature evolution, several of which, including thermal boundary resistance, are not well known. We have applied a time-resolved micro-Raman thermography technique with 10-15ns temporal resolution in order to gain unprecedented insight into the fast initial thermal transients in pulsed AlGaN/GaN devices. Different device structures and substrate materials are investigated and comparison is made to thermal simulations. We find that thermal time constants in the first 50-100ns are dominated by the thermal parameters of the GaN and not the substrate.

10:15 AM
K6, Late News

10:30 AM Break
9:30 AM

L2. Piezoelectric Actuation of All-Nitride MEMS: Katja Tonisch; Rüdiger Goldhahn; Carsten Buchheim; Volkmer Cimalla; Florentina Niebelschütz;

Few attempts to realize nitride based MEMS have been reported so far, though their piezo- and pyroelectric properties make them favourable for sophisticated solutions. We present MEMS consisting of a novel GaN/AlGaN/GaN-heterostructure. Thereby the lower GaN layer represents the mechanical active layer, while the upper GaN and AlGaN layers supply the piezoelectrically active layers for actuation and the confinement of a 2D electron gas (at the lower interface). The 2DEG serves as back electrode for the piezoelectric actuation and as read-out, since it is modulated by the mechanical oscillation. The upper AlGaN and GaN layer both contribute to the total piezoelectric response, which was determined by piezoelectric force microscopy. We studied by means of capacitance-voltage, biased Hall measurements and electrorheoactance the influence of the thickness and its ratio of both layers on the electrical field distribution in order to optimize geometry and layer structure for a maximum piezoelectric actuation.

9:45 AM

L3. AlGaN/GaN – Based MEMS with Two-Dimensional Electron Gas for Novel Sensor Applications: Florentina Niebelschütz; Volkmer Cimalla; Katja Tonisch; Christian Haupt; Klemsen Brückner; Ralf Stephan; Matthias Hein; Oliver Ambacher; Institute of Micro- and Nanotechnologies, Technische Universität Ilmenau

Novel microelectromechanical resonators structures have been realized based on AlGaN/GaN heterostructures grown on SiC substrates confining a two dimensional electron gas (2DEG), which provides a basis for sophisticated sensor structures. By means of the developed etching technology freestanding resonators were patterned without decreasing the sheet carrier concentration and electron mobility of the 2DEG inside the beams, as concluded from electrical measurements before and after the various process steps. This highly sensitive sensor system is applied for actuation as well as read out using magnetomotive and piezoelectric actuation, respectively. Due to the high sensitivity of the 2DEG and the chemical stability of the utilized materials these structures are suitable for chemical and biological sensor applications, in which the sensitivity of the 2DEG on the surrounding environment is established as additional sensing signal, for example for simultaneous measurements of the viscosity and pH – value of a nanoliter droplet.

10:00 AM

L4. Chemical Functionalization of GaN Surfaces by Hemin: April Brown; Maria Losurdo; Michael Garcia; Scott Wolter; Tong-Ho Kim; Maria Giangregorio; William Lampert; Giovanni Bruno; Duke University; IMP-CN; U.S. Army Research Office

The chemisorption and formation of self-assembled monolayers (SAMs) of hemin (a metal porphyrine) on GaN surfaces for sensing applications is presented. The chemical functionalization of GaN is achieved by using hemin solutions in DMF. The chemistry of the GaN functionalization is characterized using XPS, thickness of hemin SAMs depending on experimental conditions is determined by spectroscopic ellipsometry, and AFM is used to image the hemin self-assembling on GaN surfaces. This is the first report in literature of the kinetic (effect of time) of the GaN functionalization depending on the status of GaN surface (native oxide, wet-etched, polarity, light irradiation, etc), hemin concentration, concentration of the benzoic acid added as "spacers" in order to avoid formation of hemin aggregates that are detrimental to sensor performance. The response of the GaN-hemin to sensing few ppm of NO is also demonstrated.

10:15 AM

L5. GaN Quantum Dots as Optical Transducers in Field Effect Chemical Sensors: Olaf Weidemann; Eva Monroy; Gunther Jegert; Stefan Birner; Martin Stutzmann; Martin Eichkofl; Technical University München; CEA-Grenoble

GaN-based field-effect devices have been proven useful to detect chemically induced changes of the surface potential as the physical basis for chemical sensors in liquid or gaseous environments. For some applications, an alternative to electrical readout of the sensor signal is advantageous. To this end, GaN/AlN quantum dot (QD) nanostructures, which exhibit efficient room-temperature luminescence, allow optical detection of changes in the surface potential. We demonstrate the applicability of GaN QDs as optical transducers in chemical sensors, utilizing the optical transparency of both the sapphire substrate and the AlN matrix. GaN/AlN QD stacks were grown on conductive AlGaN:Si back-contact layers, and were equipped with catalytic Pt front-contacts. The luminescence properties of such structures and their dependence on applied electric fields have been investigated for QD ensembles with different dot sizes. The optical response of such a system towards hydrogen-containing gases is also discussed.

10:30 AM Break

Session M: MOVPE Growth of AlGaN Alloys I

Tuesday AM
Room: 313/316
Location: MGM Grand Hotel Conference Center
September 18, 2007

11:00 AM

M1. Extremely Low Dislocation Content AlN Bridge Layers on Patterned 6H-SiC Substrates by High Temperature MOVPE: Balakrishnan Krishnam; Hiroki Sugimura; Akira Bandoh; Motoaki Iwaya; Satoshi Kamiyama; Hiroshi Amano; Isamu Akasaki; Meijo University, Center of Excellence-Nano Factory; Corporate Research and Development Center, Showa-Denko K.K.

High structural quality AlN bridge layers were grown on linear trench patterned 6H-SiC substrates by high temperature MOVPE technique. Growth temperature was 1500ºC. The bridge layer formation was uniform and the coalescence was smooth up to a substrate trench width of 7.52 µm. A combination of high temperature and V/III ratio modification ensured a better transverse movement of Al species and better control of coalescence and hence extremely low dislocation content AlN was achieved. Growth rate was 6µm/h. No dislocations observed on either side of the coalescence front. The XRD omega rocking curve FWHM of symmetric (0002) and asymmetric (20-24) planes were 62 arcsec and 252 arcsec, respectively. The overall dislocation density of the AlN layer was in the order of 10^6 cm^-2 or less. A smooth step flow growth was confirmed by AFM analysis and the RMS index was 0.25 nm. The layers were crack free.

11:15 AM

M2. High-Quality AlN Buffer Fabricated on Sapphire by NH3 Pulse-Flow Multi-Layer Growth Method for Application to Deep UV-LEDs: Hideki Hirayama; Tomoaki Ohashi; Northico Kamata; RIKEN; Saitama University

We demonstrated high-quality AlN buffers on sapphire using ammonia pulse-flow multi-layer growth method by metal-organic chemical-vapor deposition (MOCVD), those are necessary for the achievement of 230-350 nm band high-brightness deep ultraviolet (UV) light-emitting diodes (LEDs) or laser diodes (LDs). We achieved crack-free, thick (3.3µm) AlN buffer with low threading dislocation density (TDD) and atomically flat surface and with stable Ga (+c) polarity. The FWHM of XRD (102) θ-2θ rocking curve was reduced from 2160 to 488 arcsec by introducing this method. The edge dislocation density of AlGaN on AlN template were 3.2×10^6 and 3.5×10^6 cm^-2, respectively. We confirmed atomically flat surface as step-flow mode observed from AFM images. We demonstrated single peaked operation of 250 nm AlGaN-based deep UV-LEDs fabricated on the AlN templates and confirmed this method is quite useful for the application to deep UV emitting devices.
Technical Program

11:30 AM
M3, Growth of Non-Polar Al_{x}Ga_{1-x}N/Al_{y}Ga_{1-y}N Multi Quantum Well Structures over m-SiC for the Fabrication of Light Emitting Devices: R. S. Khirdul Faredi; Balakrishnan Krishnan; Bin Zhang; Vinod Advairvan; Thomas Katona; Asif Khan; †Department of Electrical Engineering, University of South Carolina

Due to the absence of piezo-electric polarization fields, non-polar deep UV LEDs based on Al_{x}Ga_{1-x}N/Al_{y}Ga_{1-y}N are expected to have superior performance. M-plane AIN and SiC substrates are natural substrate choices for their growth. We report the fabrication and characterization of Al_{x}Ga_{1-x}N layers and Multiple Quantum Wells (MQWs) over m-SiC with deep UV emission from 340 to 260 nm. Initial results of a systematic study of cathodoluminescence, AFM and SEM analyses of these Al_{x}Ga_{1-x}N layers and MQWs are used to establish the feasibility of non-polar deep UV LEDs over bulk m-SiC substrates.

11:45 AM
M4, MOVPE Growth of High Quality AlN Layers and Effects of Si Doping: Sarad Thapa; Ferdinand Scholz; Joachim Hertkorn; Günter M. Prinz; Martin Feneberg; Klaus Thonke; Rolf Sauer; †Ulm University

By optimizing our MOVPE growth conditions, we have grown high quality AlN layers (rms surface roughness of 0.2 nm, HRXRD FWHM of the (002) and (104) reflections of 59 and 290 arcsec, respectively, and low temperature cathodoluminescence (CL) spectra with a FWHM of 10 meV with LO phonon replica). Further on, we studied the effects of Si incorporation on the structural and spectroscopic properties of AlN layers. Although we observed a deterioration in surface quality, much narrower HRXRD FWHM of the (002) reflection of our lightly Si doped samples could be obtained. These peaks got broader with increasing Si concentrations up to 1e19 cm-3, decreasing again for even higher concentrations accompanied by the development of cracks. HRXRD, CL, and Raman scattering measurements show that the in-plane tensile stress of our Si-doped layers increases up to Si concentrations of 1e19 cm-3, whereas a stress release is observed for higher concentrations.

12:00 PM
M5, In situ Stress Measurements during Si-Doping of AlGaN Grown by MOCVD: Jeremy Acord; Ian Manning; Xiaojun Weng; Elizabeth Dickey; David Snyder; Joan Redwing; †Pennsylvania State University

Direct measurements of SiH_{4} doping induced growth stress and dislocation bending during AlGaN growth are presented. Prior literature demonstrated that threading edge and mixed dislocations in AlGaN films bend near the AlGaN (N=0) buffer interface, leading to compressive stress relaxation and eventual tensile stress generation. This study explores SiH_{4} doping effects on stress and dislocation evolution in AlGaN investigated by in situ Multibeam Optical Stress Sensor (MOSS) measurements and post-growth cross-section Transmission Electron Microscopy (TEM). Lattice-mismatch induced compressive growth stress was measured in Al_{0.2}Ga_{0.8}N deposited on a ~85 nm AlN buffer layer on 6H-SiC. The growth stress discontinuously changed from compressive to tensile upon SiH_{4} introduction, which increased in magnitude with film thickness. The projected dislocation inclination angle within the undoped Al_{0.2}Ga_{0.8}N was 8.1±5.7°, which increased to 17.0±4.9° when SiH_{4} was introduced. These results provide direct evidence that Si-doping itself can induce dislocation bending leading to tensile stress generation.

12:15 PM
M6, Nonpolar AlN (11-20) and (1-100) Films Grown on SiC Substrates: Tetsuya Akasaka; Yasuyuki Kobayashi; Toshiaki Makimoto; †NTT Basic Research Laboratories

We report the first-ever growth of nonpolar AlN (11-20) and (1-100) films. The films were grown on SiC substrates by flow-rate modulation epitaxy (FME), wherein metalorganics and NH3 were alternately supplied, and were systematically evaluated by high-resolution X-ray diffraction (HR-XRD), secondary ion mass spectroscopy (SIMS), and transmission electron microscopy (TEM). Incorporation of boron atoms into AlN (11-20) and (1-100) films shifted the peak positions in HR-XRD to higher angles, indicating the formation of wurzite AlN (11-20) and (1-100) films, and the estimated boron concentration (~2%) by HR-XRD agreed well with SIMS results. TEM observations showed the wurzite structure of an AlN (11-20) film and the stacking fault density of 1.6E6/cm. We found that the (11-20) and (1-100) faces more effectively incorporate boron atoms into the wurzite lattice sites than the conventional (0001) face, due to their characteristic bond configurations.

11:00 AM
N1, Power AlGaN/GaN HFETs with Excellent Vb/RonQgd for High Speed Switching: Nariaki Ikeda; Kazuo Kato; Jiang Li; Syusuke Kaya; Takehiko Nomura; Mitsuru Masuda; Seikoh Yoshida; †Furukawa Electric

In this paper, in order to confirm the advantage for the high-frequency switching operation of the GaN HFETs compared with Si devices, capacitance parameters and the figure of merit (FOM) Vb/(Ron Qgd) for a switching capability were examined. We furthermore examined the switching characteristics and capacitance parameters such as an input capacitance (Ciss), a reverse transfer capacitance (Crss), a gate to a source charge (Qgs) and a gate to a drain charge (Qgd) using the GaN HFET devices with large areas with the gate width of 240 mm using a multilayer structure. The maximum drain current of 55A was obtained, and the minimum on-resistance was less than 70ohm. The breakdown voltage was obtained about 800V. As a result, a low Ciss, Crss, and Qg were obtained and the FOMs of GaN HFETs have one order of magnitude larger than that of Si power devices.

11:15 AM
N2, High Drain Current and Low Loss Normally-Off Mode AlGaN/GaN Junction HFETs with p-Type GaN Gate: Takahiro Fujii; Shogo Nakamura; Katsuoishi Mizuno; Ryota Nega; Mototaki Iwaya; Satoshi Kamiyama; Hiroshi Amano; Isamu Akasaka; †Meijo University

Normally-off-mode junction heterostructure FETs with p-type GaN gate showing high current density and extremely large on/off ratio was successfully fabricated by MOVPE. After growing p-GaN:Mg/Al_{x}Ga_{1-x}N/GaN/Undoped-NLT-buffer/Esapphire junction heterostructure, p-GaN:Mg except at the gate region was etched by RIE to expose u-AlGaN barrier layer. The fabricated device had a gate length of 2μm, a gate width of 100μm, and an interval of 8μm between the drain and the source contacts. Drain current is found to be very sensitive to surface of u-AlGaN barrier exposed by RIE etching. Reproducible and stable high drain current was achieved by very thin SiN passivation. Maximum drain current was 1.58×10^{4} [A/mm] at V_{gs}=4 [V], while the drain current at V_{gs}=0[V] is as small as 1.45×10^{4} [A/mm]. Therefore 7th orders of on/off ratio have been achieved. The sub-threshold swing was as small as 90 [mV/dec.]. The on resistance was 3.4 [mΩcm] and the threshold voltage was +0.45 [V].

11:30 AM
N3, A Normally-Off Vertical Insulated Gate AlGaN/GaN HFET: Masakazu Kanae; Masahiro Sugimoto; Narumasa Soejima; Hiroyuki Ueda; Osamu Ishiguro; Masahito Kodama; Eiko Hayashi; Kenji Itoh; Tsutomu Uesugi; Tetsu Kachi; †Toyota Central Research and Development Laboratories, Inc.; ‡Toyota Motor Corporation

We fabricated a vertical insulated gate AlGaN/GaN heterojunction field effect transistor (HFET), using a free-standing GaN substrate. i-GaN/AlN/p-GaN/n-GaN was grown on a n-GaN substrate by MOCVD. The vertical current aperture was formed by dry-etching i-GaN/AlN/p-GaN with a mask, removing the mask, and re-growing AlGaN/n-GaN. We measured the HFET with an active area of 56.5 μm x 40 μm. We have demonstrated that the HFET vertically operated with a threshold voltage of 1 V. The specific on-resistance was about 50 mΩcm. We have reduced the specific on-resistance by two orders, compared to the previous work on the vertical HFET. This is due to the suppression of the Mg-diffusion to the heterojunction.
Takehiko Nomura; Nariaki Ikeda; 1Furukawa Electric Company, Ltd.

Metal oxide semiconductor field effect transistors (MOSFETs) with trench gate structures based on GaN have been developed for the first time. These MOSFETs show excellent enhancement-mode operation with moderate threshold voltage of 5.1 V and extremely high channel mobilities of 133 cm²/Vs. The vertical structure including n-GaN/p-GaN/n-GaN layers is epitaxially grown on the sapphire substrate by conventional low-pressure MOVPE. The dry etching process is used for the formation of the trench structures, and double layered structures with SixNy and SiO2 are continuously deposited for the gate insulator by electron cyclotron resonance plasma-assisted sputtering. SixNy is relatively thin, but strongly affects the stabilization of GaN surface. This structure enables us to realize vertical switching devices with high breakdown voltages and highly integrated low on-resistance with the usage of excellent physical parameters of GaN.

12:00 PM
N5, Power Factor Correction Circuit Application Using AlGaN/GaN HFETs: Seikoh Yoshih;1 Mitsuru Masuda;1 Yuki Niiyama;1 Hiroshi Kambayashi;1 Takehiko Nomura;1 Nariaki Ikeda;1 Furukawa Electric Company, Ltd.

We demonstrate the application of a power factor correction (PFC) circuit using AlGaN/GaN HFETs for the first time. PFC circuits are important for a high efficiency power supply of homes and industries. The AlGaN/GaN HFET with a large current and a high breakdown voltage operation was fabricated. That is, the maximum drain current was over 50 A, and the minimum on-resistance was less than 70 mOhm. The breakdown voltage was over 600 V. Using these HFETs, an AC-DC converter with a power factor correction (PFC) circuit was fabricated. Irregular input AC current and voltage were converted to very smooth input signal waves AC voltage and current. The power factor was over 99%. Using this circuit, AC 100 V was successfully converted to DC 200 V, the output conversion efficiency from AC input to DC output was 93%. We thus demonstrated a good PFC circuit using AlGaN/GaN HFETs.

12:15 PM
N6, High Breakdown Voltage AlGaN/GaN Heterojunction Field Effect Transistors on Sapphire Substrates: Junxia Shi; Y. C. Choi; M. Pophristie; M. G. Spencer; L. F. Eastman; Cornell University; Velox Semiconductor Corporation

AlGaN/GaN heterojunction field effect transistors (HFETs) on sapphire substrates for high-power switching applications were fabricated using a self-align process. Without any additional field plate design, the fabricated devices with gate-drain spacing (Lgd) of 16 µm exhibited a high breakdown voltage (BV) of 1600 V with a specific on-resistance (ARon) of 5.8 mΩ·cm². This result approaches the SiC theoretical limit. The BV-ARon performance showed a linear trend with variations of Lgd, indicating a predictable performance. In addition, the effects of the source and drain contact lengths Ls and LD on ARon have also been investigated and optimized.

Session O: Sensors and Characterization II

Tuesday AM
Room: 312/317
Location: MGM Grand Hotel Conference Center

11:00 AM
O1, Analysis of Enzymatic Activity Using Functionalized AlGaN/GaN Field-Effect Transistors: Barbara Bau;1 John Howgate;1 Vedran Bandalo;1 Wiebke Steins;1 Martin Stutzmann;1 Martin Eickhoff;1 Technische Universität München

Enzyme-modified field-effect transistors (EnFETs) were prepared by immobilisation of penicillinase on AlGaN/GaN solution gate field-effect transistors. The stability of the transistor during operation in electrolyte solution and the influence of the immobilisation process on enzyme functionality have been investigated by a direct comparison of covalent immobilisation and physisorption. Covalent immobilisation by Schiff base formation on GaN surfaces modified with an aminopropyltriethoxysilane monolayer exhibits a high reproducibility with respect to the enzyme/substrate affinity. The stability of the enzyme layer is shown to be significantly increased by reductive amination of the Schiff base bonds. Further analysis was carried out with respect to the impact of environmental parameters on the sensor response. Buffer capacitance of the analyte restricts the dynamic measurement range, whereas the immobilisation process determines the response characteristics as well as stability and reproducibility of the sensor-signal. This conclusion is supported by modelling the potentiometric response of EnFETs based on penicillinase.

11:15 AM
O2, Mechanism of Surface Current in the Vicinity of Schottky Gate Formed on AlGaN/GaN Heterostructure: Junji Kotani;1 Masafumi Tajima;1 Seiya Kasi;1 Tomotsu Hashizume;1 Hokkaido University

We systematically characterized surface current in the vicinity of Schottky gates on the AlGaN/GaN heterostructure, separating it from the normal leakage current through the Schottky interface. The MOVPE-grown AlxGa1-xN/60GaN heterostructure were used. In order to detect the lateral surface current (Ip) separately from vertical current (Iv), an additional Schottky gate was fabricated parallel to the main Schottky gate with a distance (Lgg) of 200nm-5µm. The Ip was almost independent of Lgg, while the Tv drastically increased with decreasing Lgg. No temperature dependence observed in Iv, is explained by the tunneling mechanism through thin Schottky barrier. On the other hand, clear temperature dependence appeared in Ip. It is likely that other transport mechanism, e.g., a variable-range-hopping conduction, governs the surface transport. The SiN-based surface passivation drastically suppressed the surface current, indicating the surface states can play an important role for the surface transport from the gate edge.

11:30 AM
O3, Effects of Temperature on Electrical Degradation of GaN High Electron Mobility Transistors: Jungwoo Jho;1 Jesús del Alamo;1 Massachusetts Institute of Technology

Although GaN high electron mobility transistors (HEMT) exhibit great performance in RF power applications, reliability is still a big concern in this technology. In order to improve reliability, it is essential to understand physical mechanisms behind device degradation. We have carried out stress experiments to understand the effects of temperature on reliability. We have found out that the critical voltage where a device starts to degrade is reduced at high temperature. Our OFF state step stress experiments also show that catastrophic degradation starts at lower voltage at high temperature. These results are inconsistent with hot electrons related degradation mechanisms in that there would be much less hot electrons at high temperature due to enhanced phonon scattering. However, this can be understood with our previous hypothesis that device degradation results from crystallographic defect formation due to inverse piezoelectric effect as thermal energy can enhance defect formation.

11:45 AM
O4, Fabrication and Characterization of m-Plane (1-100) GaN Based Metal-Oxide-Semiconductor Capacitors: Vinayak Tilak;1 Kevin Matocha;1 Greg Dunne;1 Greg Dunne;1 GE Global Research

M-plane (1-100) non-polar, Gallium Nitride(GaN) based metal-oxide-semiconductor (MOS) capacitors were fabricated by depositing low pressure chemical vapor deposition silicon dioxide at 900°C. No positive shift in the flat band voltage of m-plane GaN MOS capacitors was observed versus temperature, confirming the absence of pyroelectric effects. In contrast, c-plane (0001) polar, GaN MOS capacitors, show a positive flat band voltage shift versus temperature and the pyroelectric coefficient of ~3X10⁻⁹ cm²K⁻¹ was measured. Smaller capacitance-voltage hysteresis was measured on m-plane GaN samples as compared to c-plane GaN samples, suggesting lower interface state density. Time dependent dielectric breakdown (TDDB) measurements are being performed and the results will be presented. We will also present results of Fowler-Nordheim tunneling measurements and estimate the conduction band offset between m-plane GaN and silicon dioxide.
Technical Program

12:00 PM
O5, A Novel Anti-Stokes Raman Scattering Technique for the Direct Measurement of Hot-Phonons in AlGaN/GaN Devices: James Pomeroi1; Martin Kuball2; M. Uren3; T. Martin4; 1University of Bristol; 2QinetiQ Ltd

GaN-based transistors are at the forefront of next-generation high-power/ frequency electronic devices. However, the role that so-called “hot-phonon” effects have on limiting their saturation velocity is not yet fully understood. Hot-phonon effects have been inferred from microwave noise-power measurements, although a direct method of probing hot phonons is preferable. We have used anti Stokes Raman scattering to measure hot-phonons in the active channel of AlGaN/GaN HFETs, enabling their localisation and temperature to be studied. Complimentary electroluminescence (EL) measurements were used to estimate a hot-electron temperature of T_e=1000K at 30V_g (24W/mm), implying a hot-phonon temperature of T_p=1000K; significantly above the 150°C lattice temperature derived from the Raman frequency shift. The temperature determined using the LO-phonon Stokes/ anti-Stokes scattering ratio, including contributions from hot-phonons and thermal equilibrium phonons in the active channel and GaN layer, respectively, is 50°C higher than the measured lattice temperature at 30Vsd, consistent with the value T_p=1000K.

12:15 PM
O6, A Novel GaN-Based Multiparameter Sensor System for Biochemical Analysis: Benedikt Luebbers1; Gabriel Kittler; Peter Ott1; Stefanie Linkohr2; Dennis Wegener1; Barbara Baur1; Michael Gebinoga1; Frank Weise2; Martin Eichhoff1; Oliver Ambacher3; 1Technical University Ilmenau; 2Institute for Physical High Technology Jena; 3Technical University of Munich; 4MacroNano®, Centre for Innovation Competence Ilmenau

GaN offers several advantages for the construction of biosensors due to its chemical stability and optical transparency. We present application examples of an AlGaN/GaN-ISFET which exhibits an inherent pH-sensitivity close to the Neuristian limit and has a very fast response time. Combined with a picoliter dosing system, an integrated micro reference electrode and an optical spectroscopy system a novel multi parameter analysis system for aqueous solutions in the micro- to nanoliter range was constructed. Titration experiments as well as the simultaneous opto-electrochemical monitoring of enzymatic reactions and measurements with functionalized enzyme-FETs in very low volumes is shown. The experimental data obtained agrees well with reference measurements performed with state-of-the-art pH-meters and spectrophotometers in 100- to 1000-fold larger volumes. These measurements show the potential of the sensor for biochemical and pharmaceutical analysis e.g. in high-throughput screening of cancer drugs.

Tuesday PM

Session P:
MOVPE Growth of AlGaN Alloys II

Tuesday PM
Room: 314/315
Location: MGM Grand Hotel Conference Center

2:00 PM
P1, A Novel MOHVPE System for the Growth of High-Quality AlGaN, \(\text{Al}_{x}\text{Ga}_{1-x}\text{N}\), Layers for Deep UV Emitters: R.S. Farreed1; K. Balakrishnan2; V. Adivarahan1; Thomas Katona1; Asif Khan1; 1University of South Carolina

We present a novel metalorganic hydride vapor epitaxy (MOHVPE) approach for the growth of III-Nitride semiconductors. In this method, MOCVD and HVPE are done in the same chamber either simultaneously or sequentially in a single growth without breaking vacuum. The system is used for depositing the device structures on non-polar r-sapphire and m-SIC, and polar c-sapphire substrates. In addition, the viability of the system for depositing m-AlN buffer layers using pulsed MOCVD over m-SIC followed by 1µ thick m-AlN layer using HVPE is reported. Characterization data will be presented for these.

3:30 PM
P2, Growth of High AlN Molar Fraction AlGaN on Selective-Area-Growth GaN: Hitoshi Miyake1; Norihiko Masuda1; Kazumasa Hiramatsu1; Mie University

High-AlN-molar-fraction AlGaN with low dislocation density was fabricated on selective-area-growth (SAG) GaN by low-pressure metalorganic vapor phase epitaxy (LP-MOVPE). To reduce threading dislocation (TD) density in the AlGaN, SAG GaN was grown on AlN/sapphire template. The structure of SAG GaN was precisely controlled by in-situ reflection monitoring. AlGaN growth was started before the coalescence of each SAG GaN to prevent crack generation during the subsequent AlGaN growth. The TD density in the AlGaN layer was 1-3×108 cm-2, which is two orders of magnitude lower than that of conventional AlGaN. The reduction of TD density is due to strain relaxation and the lateral overgrowth of AlGaN using the SAG GaN structure.

2:45 PM
P3, MOVPE Growth and Characterization of AlGaN Substrates for Ultraviolet Avalanche Photodiodes: Dongwon Yoo1; Jae Boum Limb1; Yun Zhang1; Jae-Hyun Ryu1; Shyh-Chiang Shen1; Meredith Reed2; Michael Wraab2; Russell Dupuis1; 1Georgia Institute of Technology; 2US Army Research Laboratory

AlGaN p-i-n diode based wide-bandgap avalanche photodetectors (APDs) are excellent candidates for short-wavelength photodetection in the ultraviolet (UV) spectral region \(\lambda < 290 \text{ nm}\). In this paper, we describe the growth and characterization of AlGa\(_x\)N APDs, grown on bulk GaN substrates. To achieve improved material quality of AlGa\(_x\)N, various growth parameters and schemes were studied including modulated-precursor epitaxial growth. To prevent the initiation and propagation of cracks, several strain management structure between the substrate and AlGaN layer. We also report the performance characteristics of AlGa\(_x\)N \((x \approx 0.05)\) p-i-n APD including 0.25 \(\mu\)m-thick unintentionally doped drift region. No microplasma or sidewall breakdown lumincence was visually observed. The avalanche gain reaches a maximum value of ~50 at a voltage of 86.75V. Detailed growth and material characterization of AlGa\(_x\)N p-i-n structures including TEM study and the performance of these APD devices including spectral response data will be reported.

3:00 PM
P4, Critical Issue in Growing High Quality Thick AlGaN by High-Temperature MOVPE: Naofumi Kato1; Takafumi Sumii1; Shunya Sato1; Hiroki Sagimura1; Narihito Okada1; Masataka Imura1; Motoaki Iwaya1; Satoshi Kamiyama1; Hiroshi Amano1; Isamu Akasaki1; Hisaaki Maruyama2; Hiroki Sugimura1; Narihito Okada1; Shyh-Chiang Shen1; Meredith Reed2; Michael Wraab2; Russell Dupuis1; 1Georgia Institute of Technology; 2US Army Research Laboratory

Growth of thick AlGaN on c-plane sapphire substrates was conducted by high-temperature (HT-) MOVPE. Composition of AlGaN can be controlled by growth temperature and by V/I III ratio. The use of HT-AlN template extremely improves crystalline quality of the thick AlGaN layer. In addition, crystalline-quality measured by X-ray diffraction and TEM showed that the FWHMs of X-ray rocking curves (XRCs) for both tilt and twist distributions and dislocation density in AlGaN are almost the same as those in the underlying HT-AlN template for Al composition from 0.3 to 1. A thick and crack-free AlGaN:0.89Ga0.11N layer with the FWHMs of XRCs for tilt and twist distributions as narrow as 177 arcsec. and 457 arcsec., respectively, were successfully grown. Extremely smooth and atomic-size step with a RMS surface roughness as small as 0.35 nm over a 5 \(\mu\)m × 5 \(\mu\)m scan was observed. The microstructure of AlGaN on AlN will be discussed.

3:15 PM
P5, AlGaN Distributed Bragg Reflectors in Comparison with Rugate Reflectors – Growth, Reflectivity, and Conductivity: Stephan Figge1; Timo Aschenbrenner1; Heiko Dartsch2; Detlef Hommel1; 1University of Bremen

Distributed Bragg Reflectors (DBR) are essential for the design of micro-cavity optoelectronic devices. Due to the small variation of refractive index in nitride materials at visible wave length a high composition modulation is needed to achieve reflectivity above 99%. The high aluminium content results into tensile strain and cracking of such layers. As the reflectance...
is determined by the first component of the Fourier-transform from the refractive index in general three different approaches are feasible: Step-wise variation of the refractive index (DBR), corrugated modulation (Rugate) or pulse width modulation of binary materials (needle technique). For similar reflection the Rugate structure has in comparison certain advantages such as lowest strain energy, no interfaces to be optimized, and no band offsets and therefore better vertical conductivity. In this presentation we will compare AlGaN DBRs with Rugate filters grown by MOVPE concerning growth, reflectivity and conductivity.

3:30 PM
P6, Epitaxial Growth of Non-Polar AlN Films on m-ZnO Substrates: Kohei Ueno; Atsushi Kobayashi; Jitsuo Ohata; Hiroshi Fujisaka; Hitodaka Amanai; Satoru Nagao; Hideyoshi Horie; 1University ofTokyo; 2Mitsubishi Chemical Group Science and Technology Research Center

We have grown m-plane AlN layers on m-plane ZnO substrates by pulsed laser deposition and investigated their structural properties. The direct growth of AlN on the ZnO substrates at 750°C has resulted in formation of polycrystalline materials due to serious interfacial reactions between AlN and ZnO. On the other hand, m-plane AlN has been epitaxially grown on the ZnO substrates by the use of GaN buffer layer grown at room temperature (RT). The FWHM value for AlN 1-100 XRC has turned out to be 468 arcsec. Grazing incidence angle x-ray reflectivity measurements have revealed that the heterointerface between AlN and RT-GaN is quite abrupt. XRD measurements have also revealed that the in-plane epitaxial relationship is 6.2 0001∥0001 0001∥0001. These results indicate that the use of RT-GaN makes it possible to take full advantage of non-polar ZnO substrates.

3:45 PM  Break

Session Q:
High Voltage and Advanced Device Structures II
Tuesday PM September 18, 2007
Room: 313/316 Location: MGM Grand Hotel Conference Center

2:00 PM
Q1, High Power and High Gain AlGaN/GaN MIS-HEMTs with High-k Dielectric Layer: Masahito Kanamura; Toshihiro Ohki; Kenji Imanishi; Kozo Makiyama; Naoya Okamoto; Yoshio Kikkawa; Naoki Hara; Kazuo Yoshin; 1Fujitsu Laboratories Ltd. and Fujitsu Limited; 2Fujitsu Laboratories Ltd.

In this paper, we report on the fabrication of the GaN MIS-HEMTs on the SiC substrates using the high-k Ta2O5 dielectric gate insulator for the first time. The fabricated MIS-HEMTs showed the small current collapse, the large transconductance of 200 mS/mm and very low gate-leakage current with a high breakdown voltage of 400 V. We carried out on wafer load-pull measurements for the 1 mm devices. The devices showed an output power of 9.4 W/mm and a linear gain of 23.5 dB associated with a PAE of 62%. We also investigated the RF power stability for the devices. This work was partially supported by the Ministry of Internal Affairs and Communications, Japan.

2:15 PM
Q2, Normally-Off AlGaN/GaN MOSFETs with H0, Gate Oxide: Shun Sugita; Shigeru Kishimoto; Takashi Mizutani; Masayuki Kuroda; Tetsuzo Ueda; Tsuyoshi Tanaka; 1Nagoya University, Department of Quantum Engineering; 2Nagoya University, Department of Quantum Engineering and Venture Business Laboratory; 3Semiconductor Device Research Center Semiconductor Company Matsushita Electric Industrial Company, Ltd.

Normally-off GaN MOSFETs are expected to be suitable for high-power switching systems. However, they suffer from problems of a small drain current and a small transconductance (g_m) because of a large parasitic resistance and a small gate input capacitance. In this report, we have fabricated normally-off AlGaN/GaN MOSFETs with overlap gate structure using H0, with a large dielectric constant as a gate oxide. The H0 thickness and the channel length were 100 nm and 2.5 μm, respectively. The normally-off operation with a threshold voltage of about 3 V was confirmed. The maximum transconductance was as large as 185 mS/mm and the drain current was 730 mA/mm at a gate voltage of 10 V. These results confirm the validity of the present MOSFET structure using H0, as a gate oxide for high-power switching systems.

2:30 PM
Q3, Gate Insulation and Current Collapse Suppression in InAlN/GaN HEMTs Using High-k Dielectrics: Jan Kazmierski; G. Pozzovivo; Stephan Abermann; J.-F. Carlin; M. Gonschorek; Karol Cico; K. Fröhlich; N. Grandjean; E. Bertagnolli; G. Strasser; D. Pogany; 1Technical University Vienna; 2EPFL Lausanne; 3Slovak Academy of Science, Institute of Electrical Engineering

We investigate ZrO2, HfO2 and stack of ZrO2/A12O3 as high-k dielectrics for the InAlN/GaN MOS HEMT gate insulation and surface passivation. HEMT gate geometry is 2 x 100 μm2, the source-drain spacing is 8 μm. Schottky contact-based HEMTs are prepared as a reference. The current collapse phenomenon is analyzed by pulssing the gate electrode (100 ns duration of pulses) from the base level of -10 V while keeping a constant drain bias (up-to 20 V). Results show that the gate leakage current is suppressed by 4-5 orders of magnitude by inserting the high-k dielectric. The maximal drain current of MOS HEMTs is increased to 0.9 A/mm, from 0.7 A/mm for the conventional HEMT while MOS HEMT transconductance is about the same or even increased (for ZrO2) if compared with the reference sample. We demonstrate an elimination of the current collapse after applying the high-k insulation passivation. Ultragan project no.6903 is acknowledged.

2:45 PM
Q4, Atomic Layer Etching of AlGaN/GaN Structures: Xu Zhao; Jinwook Chung; Tomas Pahelcos; 1Massachusetts Institute of Technology

GaN is one of the best candidates for high frequency and high power electronics. However, up to now, no reliable gate recess etching techniques have been reported. With device shrinking down to nanometer scale, an etching technique with atomic depth resolution is required. In this paper, atomic layer etching (ALE) of AlGaN/GaN structures is demonstrated for the first time. The etching cycle of this new technology is divided into three basic steps: first, Cl2 is adsorbed on the nitride surface; then the excess Cl2 is removed from the etching chamber; finally the remaining Cl2 is activated by a low energy Ar plasma. The etch depth of each etching cycle is exactly 1 atomic monolayer which assures an excellent uniformity and control. No increase in the surface roughness has been observed after more than 200 etching cycles. All these properties make ALE very promising as AlGaN/GaN gate recess technology.

3:00 PM
Q5, Operation Robustness of AlGaN/GaN HEMTs with an Ultrathin-Al-Layer Based Surface Control: Masafumi Tajima; Alberto Basile; Junji Kotani; Tamotsu Hashizume; 1RCIQE, Hokkaido University

The surface control process utilizing an ultrathin Al layer was proposed for the operation robustness of AlGaN/GaN HEMTs. The process consists of the treatment of the AlGaN surface using r-f excited nitrogen radicals, the deposition of an ultrathin Al layer, in situ UHV anneal at 700°C and the removal of the Al layer. The Schottky gate with the surface process showed a significant reduction of leakage current and clear temperature dependence of the I-V characteristics. For the HEMT without the surface control, the bias-temperature stress under the off-state condition brought the pronounced decrease in the drain conductance. On the other hand, no degradation appeared in the DC characteristics for the HEMT with the surface process even after the stress. The surface control process may effectively suppress the VN- and/or oxygen-related electronic levels at the AlGaN surface, thereby preventing the multiplication of surface states during the stress.
Technical Program

3:15 PM
Q6, In-Situ Passivation Combined with GaN Buffer Optimization for Extremely Low Current Dispersion and Low Gate Leakage in SiN4/AlGaN/GaN HEMT Devices on Si(111) - Marianne Germain1; Stefan Degroote1; Joff Derluyn1; Maarten Leyss2; Kai Cheng3; Jo Das4; Anne Lorenz5; Marleen Van Hove6; Denis Marcon6; DongPing Xiao7; Gustaav Borghs8; 1IMEC; 2ESAT Katholieke Universiteit Leuven

Si substrate is the sole route towards III-nitrides process on large wafer diameter: flat (Rz<90nm), crack-free HEMT epitwafers have been grown by MOVPE with diameter up to 150mm, exhibiting low sheet resistivity (260Ω/ sq.) and high uniformity (≤2%), thanks to in-situ SiN4 capping. We show here that simultaneous optimization of GaN growth and of device passivation, results in a drastic reduction of buffer and surface traps impact onto device performance, assessed by pulse IV measurements. Drain lag is correlated with the appearance of deep defect-related peaks in photoluminescence spectra (6K), and completely eliminated by tuning growth temperature (pGaN≥1042.cm). Gate formation (Ni/Au) onto MOVPE-grown SiN4, followed by cleaning and PECVD ex-situ passivation, leads to very low gate current dispersion, associated to gate leakage current in μA/mm range. Both dc and pulsed characteristics show a current density in the order of 0.8-1A/ mm, whereas maximal transconductance is 250mS/mm (Lg=1μm).

3:30 PM Break

Session R:
Optical Characterization of Lasers

Tuesday PM  Room: 312/317
September 18, 2007  Location: MGM Grand Hotel Conference Center

2:00 PM
R1, Comparison of GaInN Laser Structures Grown on Different Substrates - Alexander Dräger1; Daniel Fuhrmann1; Carsten Netzel1; Uwe Rossov1; David Schenk2; Andreas Hangleiter1; 1TU Braunschweig; 2CNRS-CRHEA

In order to get a better understanding of the influence of different substrates on nitride laser diodes we performed optical gain spectroscopy using the variable stripe length (VSL) technique on laser structures grown by MOVPE, in order to assess the effects of nonradiative recombination. We compare samples grown on sapphire, SiC, low dislocation density GaN templates, and free-standing GaN substrates. From the analysis of the gain spectra we obtain the radiative and nonradiative carrier lifetimes and find that for samples on free-standing GaN the nonradiative carrier lifetime is one order of magnitude higher than for samples grown on sapphire or SiC and even higher than the radiative carrier lifetime. Thus, the threshold current density is hardly affected by the dislocations at such low dislocation densities.

2:15 PM
R2, Wafer-Level Far Field Measurement of Blue Nitride Lasers - Dmitry Sizov1; Rajaram Bhat1; Jerome Napoleon1; Jingqiu Xi1; Herve LeBlanc1; Donald Allen1; Chung-En Zhai1; ‘Corning Incorporated

We have developed a new wafer-level laser test (WLT) method to measure far field patterns (FFPs) for lasers on a transparent substrate based on the scattered light collection from the bottom of substrate. The advantage of this method is that it requires less equipment resources as compared with other WLTs and needs only a CCD camera to determine FFPs by analyzing the image formed by the scattered lasing light. This avoids the Lloyds mirror reflection effect of the wafer surface. The images are analyzed using quasi-geometrical optics and characteristic matrix approach. Horizontal FFPs of 400-440 nm InGaN lasers were determined with angular accuracy better than 1 degree. The lateral mode structure dependence on operating current and geometrical stripe widths was revealed. This method is helpful for both crystal growth and fabrication development and could be used in any other semiconductor system where the substrate is transparent at lasing emission wavelength.

2:30 PM
R3, Non-Radiative Recombination Centers in InGaN Lasers - Marc Schilliglais1; Angar Laubsch1; Stephan Lutgen1; Adrian Avramescu1; Georg Bridler1; Desiree Queren1; Uwe Strauß1; ‘OSRAM Opto Semiconductors GmbH

The analysis of electroluminescence intensity as a function of current density was used as feedback tool to reduce non-radiative recombination centers (NRC) in InGaN-lasers. The influence of indium content of InGaN-barriers on the NRC density, as well as the influence of a contamination of the quantum well, e.g. by magnesium, was studied in detail. The reduction of non-radiative recombination led to an improvement of laser performance. We report a threshold current density of 1.4 kA/cm2 and a slope efficiency of 1.11W/A for a 10μm wide ridge-waveguide (RWG)-laser at 432nm.

2:45 PM
R4, Inhomogeneously Broadened Optical Gain Spectra of InGaN Quantum Well Laser Diodes - Kazunobu Kojima1; Mitsuru Funato1; Yoichi Kawakami1; Harald Braun2; Ulrich Schwarz2; Shinishi Nagahama2; Takashi Mukai1; 1Kyoto University; 2Regensburg University, ‘Nichia Corporation

Optical gain spectra of near-UV, violet, blue and aquamarine InGaN laser diodes, oscillating at 375, 407, 440, and 470 nm, respectively, are obtained under electrically driven condition. The near-UV and violet lasers, whose inhomogeneous broadening factors are less than or comparable with homogeneous ones, show a superlinear and linear behavior for their maximum mode gains, respectively, while the blue and aquamarine diodes with high inhomogeneous values are sublinear. Furthermore, against our expectations, longer laser diodes reveal higher mode gain below 1 kA/cm2 of injected current density. Explaining this fact, two different gain models are compared; one assumes globally constant carrier density in quantum well, and the other model is based on local constant quasi-Fermi levels for both electrons and holes. The latter model predicts in agreement with the higher gain at low carrier densities for laser diodes with low inhomogeneous broadening factors.

3:00 PM
R5, Laser Threshold and Optical Gain of Blue Optically Pumped InGaN/GaN MQW Lasers Grown on Si - E.V. Lusenko1; A.V. Danilchyk2; N.P. Tarasuk2; V.N. Pavlovski2; A.L. Guriskii2; G.P. Yablonskii2; H. Kalisch3; R.H. Jansen3; Y. Dikme3; B. Schineller2; M. Heeske3; ‘National Academy of Sciences of Belarus; ‘RWTH Aachen; ‘AIXTRON AG

Optical and laser properties of a series of MQW heterostructures grown on silicon with Al prediposition were investigated. Photoluminescence (PL) band positions covered a spectral range of 430 – 460 nm under L0 = 1 MW/cm2 and 445-505 nm under L0 =0.15 W/cm2. Lasing was achieved under transversal optical pumping at room temperature using only cleaved lateral facets of the samples as mirrors. The laser threshold risetime monotonically from 137 kW/ cm2 to 300 kW/cm2 with a laser wavelength increase from 440 nm to 465 nm. A numerical simulation of the laser conditions shows that the minimal threshold is realized on the fifth order mode. However, the calculated value of material optical gain of InGaN at the threshold neglecting the additional internal losses increases only from 750 cm-1 to 1020 cm-1, mainly due to an absorption rise in the substrate with increasing wavelength. A correlation was observed between PL characteristics and laser threshold.

3:15 PM
R6, Comparison of Scanning μ-Electro- and μ-Photo-Luminescence Spectroscopy of Blue InGaN LEDs on Si(001) and Si(111) - Lars Reissmann1; Fabian Schulze1; Armin Dadgar1; Jürgen Christen1; Alois Krost1; ‘OvG University Magdeburg

We report on scanning micro-electroluminescence (μ-EL) and micro-photoluminescence (μ-PL) spectroscopy measurements on LEDs on Si(001) and Si(111) substrate. Both, μ-EL and μ-PL were performed in the same setup. For PL excitation, the 324 nm line of a He-Cd-laser was used. The LEDs were driven by constant currents of up to 200 mA. During measurements, the identical surface areas were scanned. For the LED grown on Si(001), the PL-peak wavelength is blue-shifted compared to the EL-peaks. The positions of the extrema of FP-interferences also shift, evidencing change of refractive index with injection current. With increasing currents the EL-peak
further red-shifts indicating heating. While PL peak wavelength randomly fluctuates, significant large domains of identical EL peak wavelength of 30-50 μm size appear under current injection (50mA). Obviously the effect of local In-fluctuation becomes extinguished by the high carrier densities injected. An LED on Si(111) used as reference also shows blue-shifted PL-peak wavelength.

3:30 PM Break

**Technical Program**

**Session S: Quantum Dots: Characterization**

**Tuesday PM**
**September 18, 2007**
**Room: 314/315**
**Location: MGM Grand Hotel Conference Center**

**4:00 PM**
**S1, Excitonic Structure of Single Polar Stranski-Krastanov GaN/AlN Quantum Dots: Dobri Simeonov1; Amelie Dussaigne1; Raphael Butè2; Nicolas Grandjean1; 1École Polytechnique Fédérale de Lausanne (EPFL)**

The optical properties of single GaN/AlN quantum dots (QDs) have attracted much attention but thorough spectroscopic studies are usually limited by the large QD density as well as by the spectral diffusion. Here we report a study on single polar Stranski-Krastanov GaN/AlN QDs grown by molecular beam epitaxy. Growth conditions promoting low density and large dispersion size have been used. 200 nm circular mesas have been etched allowing single dot to be isolated. Low temperature microphotoluminescence studies have been performed. The typical linewidth of single dot PL peaks is around 1 meV while the narrowest is about 700 μeV, the lowest linewidth reported so far for polar GaN/AlN QDs. Biegaint emission was equally observed with binding energy of ~ 3 meV, as well as excited states. An exhaustive study of the dot behavior on temperature, power, and polarization will give more insights on the physics operating in such systems.

**4:15 PM**
**S2, Linear Polarization of the Emission of a Single Polar GaN/AlN Quantum Dot: Richard Bardoux1; Thierry Guillet1; Pierre Lefèvre1; Thierry Taliercio1; Thierry Bretagnon1; Fabrice Semond1; 1Groupe d’étude des semi-conducteurs, Centre de Recherche pour Hétéro-Epitaxie et ses Applications - CNRS**

We report on polarization-resolved micro-photoluminescence experiments performed on a single GaN/AlN polar quantum dot (QD) grown on Si(111) substrate. We have performed a systematic study of about 50 QDs. The emission of about half of the QD excitons is strongly linearly polarized, up to 90%. Such a polarization is known to be the signature of the asymmetry of the QD shape, which lifts the degeneracy of the optically active excitons. However in the case of our GaN QDs, the polarization angles are widely distributed and do not follow the crystallographic axes, and the sharp transition lines of each QD do not appear as doublets of cross-polarized peaks. The fine structure of GaN QD excitons therefore presents strong differences with the well understood one of InAs and CdTe QDs.

**4:30 PM**
**S3, Spatially Resolved Luminescence Spectroscopy of Single GaN/AlGaN Quantum Disks: Uwe Jahn1; Jelena Ristic1; Enrique Calleja Pardo2; 1Paul-Drude-Institut für Festkörperforschung; 2EPFL-SB-IPEQ-LOEQ; 1ETSI Telecommunication, Universidad Politecnica**

Using spatially resolved cathodoluminescence, we have measured the spectral and spatial distribution of the luminescence intensity of GaN/AlGaN nanodots containing GaN quantum disks grown by plasma-assisted MBE on a Si(111) substrate. The full width at half maximum of the line quantum of the disk is as large as 130 meV even for single nanodots. This broadening, which is about four times larger as compared with corresponding quantum wells, can be partly caused by inherent optical properties of such mesoscopic structures due to a laterally inhomogeneous distribution of strain. This strain distribution depends on the geometrical conditions, in particular, on the ratio of the diameter and the thickness of the disks. Therefore, the strain distribution can counteract the advantage of a defect-free growth of nanodots, i.e., a proper choice of thickness and diameter of the disk is important for the employment of such columnar heterostructures in optoelectronic-device applications.

**5:00 PM**
**S5, Spin Relaxation in GaN/AlN Self-Assembled Quantum Dots: María Garmo1; Jose Llorens2; Alberto García-Cristóbal3; Anna Vinattieri3; Massimo Gurioli2; Bruno Daudin3; 1Universidad de Valencia; 2Università di Firenze; 3CEA-Grenoble**

The spin dynamics of MBE-grown wurtzite GaN self-assembled quantum dots (QDs) has been investigated by means of time-resolved photoluminescence performed under nearly resonant excitation. The degree of polarization of the emission, either circular or linear, drops to zero in a time scale faster than the 40-ps time resolution of the experiment. This opposes the long lived polarization found in InAs QDs, where the spin is totally frozen over the exciton lifetime. The experimental results are analyzed with the aid of electronic structure theoretical calculations for QDs of realistic shape. It is found that the large internal electric field reduces drastically the effective strength of electron-hole exchange interaction which should lead to long spin decay times. However, the strong mixed character predicted for the hole excited states should hinder the creation of a well defined spin polarization for excitation energies above resonance, which could explain the fast dynamics found experimentally.

**5:15 PM**
**S6, Temperature Dependence of the E2h Phonon Mode in Wurtzite GaN/AlN Quantum Dots: Jorge Badagovsky1; Ana Croś2; Alberto García-Cristóbal3; Andrés Cantarero3; Bruno Daudin3; 1CMUV-University of Valencia; 2Università di Firenze; 3CEA-Grenoble**

The temperature dependence of phonon frequencies in semiconductors is commonly described in terms of a combination of anharmonic processes (two- and three-phonon decay) and thermal expansion effects. Concerning the E2h phonon mode, anharmonic effects in bulk AlN are dominated by two phonon decay channels; in bulk GaN, interestingly, three phonon decay channels are allowed. Our goal in this work is to analyze the influence of confinement on the phonon decay channels of GaN/InGaN-QDs. By means of Raman scattering, we investigate the temperature dependence of the E2h phonon mode from 88 to 650 K. For the analysis of the experimental data it is necessary to take into account the thermal mismatch between the dot and the AlN spacer, as well as phonon anharmonic effects. It is found that the changes induced by confinement in the phonon dispersion are not enough to introduce new decay channels in the phonon recombination process.
Technical Program

**Session T:** Nonpolar and Semipolar Materials and Devices I

**Tuesday PM**

**September 18, 2007**

Room: 313/316

Location: MGM Grand Hotel Conference Center

**4:00 PM Invited**

**T1, Growth and Properties of Non-Polar Nitrides on Various Substrates:**

*Hiroshi Amano*; Daisuke Iida; Takeshi Kawashima; Motoaki Iwaya; Satoshi Kamiyama; Isamu Akasaki; 1Meijo University

Nonpolar GaN grown on lattice mismatched substrates is rich in microstructures such as dislocations, stacking faults and inversion domains. These defects induce nonradiative recombination centers thereby affecting the efficiency of the fabricated light-emitting diodes. One-side-wall-seeded epitaxial lateral overgrowth on different substrates is found to be effective to reduce the density of threading dislocations and stacking faults and to realize low cost fabrication of LEDs. The mobility of electrons in n-type GaN:Si is improved by reducing the defect density. In comparison, conductivity control of p-type nonpolar GaN is much more feasible compared with that of c-plane GaN. A GaN:N:GaN multi-quantum-well structure can be successfully grown on low-dislocation-density nonpolar GaN. The performance of the visible LEDs fabricated on nonpolar GaN was characterized. The reduction of defects is found to be essential for the improvement of the efficiency of visible nonpolar LEDs.

**4:30 PM**

**T2, Improved Electroluminescence on m-Plane InGaN LEDs:**

*Matthew Schmidt*; Kwang-Choon Kim; Zhongyuan Jia; Hitoshi Sato; Natalie Fellows; Hisashi Masui; Makoto Saito; Kenji Fujito; Shuji Nakamura; Steven DenBaars; James Speck; 1University of California, Santa Barbara; 2Mitsubishi Chemical Corporation

We report on the growth and fabrication of high power and high efficiency nonpolar m-plane GaN light emitting diodes (LEDs) grown by metal organic chemical vapor deposition (MOCVD) on low defect density bulk m-plane GaN substrates. Several growths were performed to optimize the multiple quantum well (MQW) structure, such as varying the number of wells, well thickness, barrier thickness, and growth temperature. The processed LEDs were diced and packaged using both a standard epoxy technique and an advanced optic for high light extraction efficiency. Both DC and pulsed testing were performed. Quantum well thicknesses of up to 20 nm showed good performance, which has never been observed on c-plane devices. Using an advanced optic and under pulsed testing (1% duty cycle, 28 mW and an external quantum efficiency (EQE) of 45.4% was achieved at 20 mA drive current and a peak emission wavelength of 402 nm.

**4:45 PM**

**T3, Mg Doping of m-Plane and c-Plane GaN in MOCVD Growth Conditions:**

*John Northrup*; 1Palo Alto Research Center

The m-plane is now receiving attention as a possible substrate for growth of nitride-based optoelectronic devices because of the absence of polarization fields in quantum wells grown on this surface. An important question is how the doping efficiency on the m-plane compares with dopant incorporation on other surfaces, such as the c-plane. This issue has been investigated for the case of Mg, which dopes GaN p-type by substituting for Ga. First principles calculations of formation energies for Mg on these surfaces in conditions corresponding to MOCVD growth indicate that there is an advantage to growth on the m-plane: Under the same growth conditions the formation energy of surface MgGa complexes is lower on the m-plane in comparison to the c-plane. The origin of this difference in stability will be discussed.

**5:00 PM**

**T4, Sidewall Epitaxial Lateral Overgrowth of Nonpolar GaN by Metalorganic Vapor Phase Epitaxy:**

*Daisuke Iida*; Takeshi Kawashima; Motoaki Iwaya; Satoshi Kamiyama; Hiroshi Amano; Isamu Akasaki; 1Meijo University

Major obstacles to achieving high-performance devices using nonpolar a-plane and m-plane GaN are very high density threading dislocations and stacking faults. Low-defect-density nonpolar plane GaN films were successfully grown by sidewall epitaxial lateral overgrowth (SELO) using metalorganic vapor phase epitaxy (MOVPE). In this study, we control the growth rate ratio of Ga-polar GaN to N-polar GaN by controlling the V/III ratio and temperature during growth. Control of the V/III ratio is found to be very important in achieving the growth of GaN from only one c-plane sidewall. It was possible to grow GaN only from N-face sidewall of the grooves by maintaining a high V/III ratio, which reduces the number of coalescence regions on grooves and decreases threading dislocation density and stacking fault density. Therefore, we can achieve one-side seeded epitaxial lateral overgrowth (OSELO).

**5:15 PM**

**T5, Defect-Mediated Surface Morphology of Nonpolar m-Plane GaN:**

*Asako Hirai*; Benjamin Haskell; Melvin McLaurin; Feng Wu; Steven DenBaars; Shuji Nakamura; James Speck; 1University of California, Santa Barbara

The role of extended defects in determining the atomic scale surface morphology of nonpolar [1-100] m-plane gallium nitride has been elucidated. The heteroepitaxially grown m-GaN films are commonly reported to yield striated surface morphologies (slate morphology) correlated with their high densities of basal plane stacking faults (SF). Here, the growth window was explored to allow non-slant morphologies for hydride vapor phase epitaxy. Lateral epitaxial overgrowth with the stripe orientations parallel to the [1-20] a-direction was then utilized to produce m-GaN films with three regimes of different extended defect contents, i.e., both threading dislocations (TDs) and SFs on window regions, only SFs on N-face wing regions, and neither TDs nor SFs on Ga-face wing regions. We have found that the elimination of SFs from the m-GaN yielded step-flow features with an average step height of 4 – 7 monolayers even for slate morphology growth conditions.
Technical Program

Poster Session II
Tuesday 5:30-7:00PM
Room: Prefunction Area
September 18, 2007
Location: MGM Grand Hotel Conference Center

E-Devices: Device Characterization

Effects of Fluorine Bombardment on the Electrical Characteristics of AlGaN/GaN High Electron Mobility Transistors: Anirban Basu; Vipan Kumar; Ilesanmi Adesida; Michael Iza; Hong Zhong; Noble Johnson;

A comprehensive study on the effects of fluorine bombardment on the electrical characteristics of AlGaN/GaN HEMTs will be presented. Prior to gate metallization, bombardment with fluorine ions in the gate region has been shown to increase the threshold voltage of the fabricated transistors to positive values thereby yielding E-mode HEMTs. Accumulation of fluorine atoms has been detected in the two-dimensional electron gas channel under certain bombardment and annealing conditions. However, a systematic study of the effects of fluorine bombardment on device characteristics is still absent. Our results, at room temperature and at 77K, show that significant amount of sheet concentration and mobility modulation is possible through fluorine bombardment, which in turn seriously affects the electrical characteristics of fabricated devices. Device-related results along with analytical data will be presented to demonstrate the effects of fluorine that is crucial to the performance of high electron mobility transistors.

7th International Conference of Nitride Semiconductors
Tuesday PM

Technical Program

High Temperature Behavior of GaN HEMT Devices on Si(111) and Sapphire Substrates: Roberto Cuero1; F. Calle1; A. F. Braha1; Y. Corder1; M. Azize2; N. Baron3; S. Chenot4; E. Muhou4; 1Institute of Optoelectronic Systems and Microtechnology and Department of Electronic Engineering - Superior Technical School of Engineers of Telecommunication (Polytechnical University of Madrid); 2Research Center on the Hetero-Epitaxy and its Applications-National Scientific Research Center; 3Research Center on the Hetero-Epitaxy and its Applications-National Scientific Research Center, Picosgipa International

The study of GaN HEMT devices at high temperatures (HT) is necessary to understand and optimize their behaviour. Drain current (I_D) and transconductance (g_m) measurements, on single-gate transistors on Si(111) and sapphire with different gate lengths, were carried out from room temperature (RT) up to 350°C. All devices show lower characteristics as they are heated, mainly due to the electron mobility reduction. Nevertheless, devices recover their initial properties after the thermal cycling. Near RT, HEMTs on Si(111) present better performance than transistors on sapphire, but as temperature increases differences disappear. Therefore, it seems that substrate thermal conductivity becomes irrelevant at HT. Gate lengths and drain-source distances play also a significant role in HT performance. The relative reduction in I_D and g_m with temperature is lower for compact devices; related with the operation point of the device, from the linear regime towards the saturation region as the gate length is shortened.

Influence of Surface Preparation and p-AlGaN Thickness on Electrical Properties of p-AlGaN/GaN Heterostructures: Takayuki Sawada1; Kensuke Takahashi1; Kazumichi Imai1; Kazuhiro Suzuki1; Naohito Kimura1; Kazutaka Kitamori1; 1Hokkaido Institute of Technology

Recently, fabrication of E-mode AlGaN/GaN HEMT is attracting much interest. For this purpose, a recess gate structure is employed. However, Si(111) and sapphire with different gate lengths, were carried out from room temperature as the gate length is shortened. To optimize the device performance, both electron transmission probability through the GaAs/GaN interface potential barrier and the avalanche breakdown voltage are calculated with respect to the setback thickness. The device gain dependence on the setback layer doping type has also been investigated.

Performance Stability of AlGaN/GaN HEMT: Effect of Plasma Processing: Tamara Baksht1; Yaron Knafo1; Lina Ortenberg1; Ilanit Yehuda1; Joseph Kaplan1; Gregory Bunin1; 1Tel Aviv University

Effect of plasma processing on the performance stability of AlGaN/GaN HEMTs was systematically investigated. Fluoride-based plasma treatment have lately been used for enhancement mode GaN HFETs. Physical mechanism of fluoride plasma treatment proposed in the past to be F- ions implantation to AlGaN layer. In the present work, electrical properties of bare p-AlGaN/GaN and Ni/p-AlGaN/GaN Schottky samples prepared by wet-etching of the AlGaN layer have been systematically investigated. Hall effect measurements of bare p-AlGaN/GaN samples indicated that the surface oxide increases 2DEG density, while the thinner the AlGaN layer, the lower the 2DEG density, accompanied with reduced electron mobility. Both forward and reverse currents of Ni-Schottky samples increased with reducing the AlGaN layer, giving smaller effective SBHs. The dependence of the effective SBH on the AlGaN thickness can be reproduced by considering combined leakage currents due to leaky patches with a low SBH and simple tunneling through the surface barrier.

E-Devices: High k and Advanced Devices

AlGaN/GaN-HFET with AlOx Gate Insulator Formed by MOCVD: Hiroyuki Sazawa1; Naohiro Nishikawa1; Yoshiaki Honda1; Masahiko Hata1; Mitsuaki Shimizu1; Hajime Okumura1; Takeaki Sakurai1; Katsuhiro Akimoto1; 1Sumitomo-Chemical Company, Ltd.; 1National Institute of Advanced Industrial Science and Technology; 1University of Tsukuba

We report on metal-insulator-semiconductor (MIS) heterostructure field-effect transistor (HFET) with AlOx gate insulator formed by the metal-organic vapor deposition (MOCVD) method designed for achieving low gate leak current and less current collapse. The AlOx insulator was deposited successively onto the AlGaN/GaN from trimethylaluminum (TMA) and n-butyl ether. Gas flux during the AlOx/AlGaN interface formation was mainly consisted of ammonia and nitrogen with the aim of preventing nitrogen vacancy creation on the AlGaN that could lead to the gate leak and the current collapse. The fabricated devices were evaluated under direct current operation. The gate leakage current of the MIS-HFET was three orders of magnitude lower than that of conventional HFET. The change in transition drain current measured as a function of time after switching drain bias was found to be smaller in the MIS-HFET than in the HFET. Advantages of the AlOx gate insulator in MIS-HFET fabrication were demonstrated.
AlInN/GaN HEMTs on Sapphire: DC and Pulsed Characterisation: Michael Fieger; Martin Eickelkamp; Wanjiao Zhang; Lars Rahimzadeh Koshoor; Christof Mauder; Yilmaz Dikme; Michael Heucken; Achim Noculak; Holger Kalisch; Rolf Jansen; Andrei Vescan; - RWTH Aachen University; 1AIXTRON AG

AlN, InN, N/GaN high electron mobility transistors (HEMTs) grown by MOCVD on sapphire substrates were examined regarding their electrical characteristics. A sheet carrier concentration n_s of ~2.6 × 10^{13} cm^{-2} and a peak mobility μ of 1410 cm^{2}/(Vs) extracted by room temperature (RT) Hall measurements indicate the good properties of the two-dimensional electron gas (2DEG) at the heterointerface. Outstanding ohmic source and drain contacts with R_s of 0.3 Ω and sheet resistances R_n as low as 235 Ω/sq provide the basis for good electrical characteristics of our HEMT devices (L_g = 1 μm, W_g = 50 μm and 5 μm source-drain spacing). A low knee voltage V_{knee} of 5 V and a peak transconductance g_m of 243 mS/mm were achieved. At V_{gs} = 2 V a maximum drain current density I_{dss} of 1.28 A/mm was measured. Without passivation, pulsed DC I-V measurements revealed reduced dispersion compared to AlGaN/GaN HEMTs.

Close Lattice-Matched AlInN Based Heterostructures for High Power Electronics: Marcus Gonschorek; Jean-François Carlin; Eric Feltin; Marcel Py; Nicolas Grandjean; - Ecole Polytechnique Federale de Lausanne (EPFL), Switzerland

Owing to the possibility of growing AlInN lattice-matched on GaN for an Indium composition of ~17.5% while keeping a large band-offset and discontinuity in spontaneous polarization, AlInN alloy appears to be suitable for designing high electron mobility transistors. From the differences in spontaneous polarization across the lattice-matched AlInN/GaN heterostructure one expects a polarization induced sheet charge density of 0.416 C/m^{2} resulting in a two dimensional electron gas (2DEG) density of n_s ~2.6 × 10^{13} cm^{-2}. This value is confirmed by capacitance-voltage and Hall measurements. Since the lateral transport is mainly limited by the poor quality of AlInN/GaN interface, a thin AlN interlayer was inserted resulting in a record mobility of ~1200 cm^{2}/Vs at 300 K. Based on this optimized lattice-matched heterostructure, the 2DEG transport properties are investigated in near-lattice-matched composition range from ~6.9% to 19.7% leading to a n_s of ~4.0 × 10^{13} cm^{-2} and ~2.2 × 10^{14} cm^{-2}, respectively.

Comparative Studies on AlGaN/GaN MOS-HEMTs with High-k HIO, or Epitaxial ScO,Gate Oxide: Chang Liu; Eng Fong Chor; Leng Seow Tan; - National University of Singapore

AlGaN metal-oxide-semiconductor high electron mobility transistors (MOS-HEMTs) with reactive-sputtered high-k HIO, or pulsed-laser-deposition-grown epitaxial ScO,Gate oxide were investigated. The ScO,GATE/HEMT system exhibited better interface properties, including larger conduction band offset (2.04 eV) and smaller effective oxide charge density as the second sample, except that Si-delta doped layer was inserted between channel and p-GaN layer [sample3]. The drain leakage current of sample 2 was greatly reduced by adopting p-GaN backbarrier at least one order lower compared to the conventional heterostructure (sample1). The Si delta-doped layer inserted at the junction interface (sample3) can sufficiently alleviate the channel depletion from the formation of pn junction and even further it can supply extra electrons into the channel, which greatly increase drain current by a factor of 4 compared to that of sample 2.

Effects of Surface Passivation Films on AlGaN/GaN HEMT Structure: Shuichi Yagi; Mitsuaki Shimizu; Toshioide Ide; Hajime Okumura; Yoshihiko Yano; Nakao Akutsu; - AIST; 1Taito Nippon Sanso Corporation

The effect of the high-k insulator passivation on the sheet resistance of the AlGaN/GaN heterojunction structure was investigated. The sheet resistance was reduced after the deposition of the high-k insulator films. In the case of the HEMT device operation, when the high-k material is used as MIS gate insulator, we found the changes in the gate threshold voltage. With the help of the recess gate structure, the normally-off mode operation can be achieved using high-k MIS gate structure.

High-Mobility Ultrathin AlN/GaN and AlN/AlN/GaN Heterojunctions Grown by MBE: Yu Cao; Keija Wang; Debdeep Jena; - University of Notre Dame

Due to the large polarization difference between AlN and GaN, a high 2DEG density can be achieved with a very thin AlN layer. This results in larger transconductance, and lower threshold HEMTs. A peak extrinsic transconductance of 211 mS/mm was reported when the AlN/GaN HEMT had the electron mobility of only 365 cm^{2}/Vs indicating that the performance can be greatly enhanced with ultrashallow AlN/GaN heterojunctions with mobilities exceeding 1000 cm^{2}/Vs. A series of AlN/GaN heterojunctions with high electron mobilities have been grown by MBE with the AlN layer thickness varied from 1nm-8nm. The highest mobility was ~1200 cm^{2}/Vs (300K) and ~4000-5000 cm^{2}/Vs (77K). To reduce the gate leakage, AlN/AlN/GaN heterojunctions was grown with the 2DEG mobility of ~1100 cm^{2}/Vs (300K) and ~3400 cm^{2}/Vs (77K), where the sheet charge density is ~3e12 cm^{-2}. The structural and transport characterization of the ultrashallow 2DEG heterojunctions and their device applications will be presented.

Influence of GaN Capping on Performance of InAlN/AiN/GaN MOS-HEMTs with Al2O3 Gate Insulation Prepared by CVD: Gianmauro Pozzovivo; Jan Kuzmik; Sebastian Golka; Karol Cico; Karol Frohlich; Jean Francois Carlin; Nicolas Grandjean; Werner Schrenk; Gottfried Strasser; Dionyz Polygan; - Technical University Vienna; 1Academy of Science of Bratislava; 1EPFL Ecole polytechnique Federale de Lausanne

We investigate InAlN/AiN/GaN-based MOS-HEMTs with and without a 2nm GaN capping below an Al2O3-insulator. An excellent reduction of the leakage current, up to 6 orders of magnitude, is observed in MOS-HEMT structures compared to Schottky-based-HEMTs, both with GaN capping. In the case of uncapped samples the reduction in the leakage current is 3 orders of magnitude. The maximal transconductance value gm,max for the GaN-capped-MOS-HEMT is about 10% higher than that for the conventional Schottky-based-HEMT, while in the case of uncapped devices gm,max is about the same for both Schottky and MOSHEMT. Similarly the maximal-drain-current in the case of GaN capped MOSHEMT is 950mA/mm exhibiting increase of 170mA/mm in comparison to the corresponding conventional Schottky-based-HEMT. We demonstrate that a GaN-cap between the InAlN-barrier and the Al2O3-insulator the AI2O3-film leads to the additional improvement of performances in terms of gate leakage current reduction, and to the IDS and gm,max increase. Ultragran-project, contract no. 6903 is acknowledged.

Interface Characterization of ALD Deposited Al2O3 on GaN by CV Method: Clemens Ostermaier; Hwa-Chul Lee; Sun-Young Hyun; Sang-II An; Ki-Won Kim; Hyun-Ick Cho; Jong-Bong Ha; Jung-Hee Lee; - Kyungpook National University; 1Korea Electronics Technology Institute

We report on the optimal device structure to increase carrier confinement and suppress the buffer leakage current by three kinds of samples. First sample, conventional HFET structure with high-resistive(HR) GaN layer was grown [sample1]. The second sample was grown by utilizing (1um) p-GaN layer instead of HR-GaN [sample2]. Third sample is exactly the same as the second sample, except that Si-delta doped layer was inserted between channel and p-GaN layer [sample3]. The drain leakage current of sample 2 was greatly reduced by adopting p-GaN backbarrier at least one order lower compared to the conventional heterostructure (sample1). The Si delta-doped layer inserted at the junction interface (sample3) can sufficiently alleviate the channel depletion from the formation of pn junction and even further it can supply extra electrons into the channel, which greatly increase drain current by a factor of 4 compared to that of sample 2.
Technical Program

change to be around 800°C. Then we characterized the interface charges of both films according to the flatband shift induced by over-bandgap light, showing the lowest interface charge density of 1.27e12 cm-2 after thermal treatment at 850°C. Additionally, we measured the AC conductivity from 200 Hz to 20 kHz and calculated the interface states density ( Dit) of the upper half of the GaN bandgap, showing the lowest Dit of 1e10 cm-2eV-1 at 2 eV above valence band, while it remains higher round the band edge at 1.1e11 cm-2eV-1, for annealing at 750°C.

MBE Grown AlInN and AlInN/GaN FETs: Huili (Grace) Xing; Tom Zimmermann; David Deen; Yu Cao; Debedee Jena; 1University of Notre Dame

AlInN has been predicted to be well suited for the barrier layer in AlInGaN-based HEMTs. AlInN lattice matched to GaN might be beneficial in improving carrier confinement as well as strain induced reliability issues, and small variations in the composition ratio (In/Al) allow one to introduce compressive or tensile strain relative to GaN thus tuning the polarization induced charges without having to compromise the benefits from large bandgaps of Al-rich AlInN. Recently in our lab, various AlInN structures have been investigated by MBE growth as well as the resultant AlInN/AlN/GaN HEMTs. For example, an AlInN/AlN/3nm GaN structure showed a sheet charge of ~ 3.2e13 cm-2 and mobility of ~ 1100 cm2/Vs at RT and ~ 3e13 cm-2 and mobility of ~ 3400 cm2/Vs at 77K; and the resulting HEMT showed a maximum current of ~ 1.4 A/mm. The detailed findings on material growth, quality and devices will be presented.

New GaN-Based MOS-HEMT Structures with Record Device Performance: Amir Dabiran; Andrei Osinsky; Andrew Wowchak; Brian Herton; Junqing Xie; Peter Chow; 1SVT Associates

AlGaN/GaN-based high electron mobility transistor (HEMT) structures, with high (>75%) Al contents, were grown on sapphire and SiC substrates by RF plasma-assisted molecular beam epitaxy (MBE). Using high Al compositions allowed efficient electron confinement with thin ( < 10 nm) AlGaN barrier layers. The highly strained AlGaN layers induced very high sheet electron densities (> 2e13 cm-2), while the controlled growth of high quality AlGaN/GaN resulted in high room-temperature electron mobility values (> 1700 cm2/Vs.). The combination of very high values of electron sheet density and mobility resulted in record sheet resistivity values of < 180 ohm/square. We will present the DC and RF characterization of metal-oxide-semiconductor heterojunction field-effect transistors (MOSHET) exhibiting lower leakage currents, improved drain currents, higher positive operational voltages and better rf-properties than HFETs. On the other hand, they suffer from a loss in channel control due to the additional oxide-capacitance. As a solution, we utilized the rare-earth scandate GdScO3 to isolate the gate. Due to its high dielectric constant (>20), the control of the MOSHETs can be enhanced. For our experiments, 1.5μm GaN- and 30nm AlxGa1-xNy were grown on sapphire by MOCVD. Diodes and transistors were fabricated using standard technology, for mesa, ohmic contact, and gate processing. For MOS devices, GdScO3 was deposited by electron beam evaporation and subsequently annealed. De- and rf-measurements showed that by incorporating GaN/AlGaN/GaN MOSHFET, respectively. From the intrinsic transconductance evaluated using measured data of density of states(DOS) and channel length modulation(LM), the extrinsic transconductance can be well fitted using measured data of roll-off and series resistance. The series resistance is found to be 10 and 5.8 Wmm for the HFET and MOSHFET, respectively. From the intrinsic transconductance evaluated using measured data of roll-off and series resistance. The series resistance is found to be 10 and 5.8 Wmm for the HFET. 

 Optimization of GaN MOS Capacitors and FETs: Weixiao Huang; Tahir Khan; T. Paul Chow; 1Rensselaer Polytechnic Institute; 2Freescale Semiconductor

In this paper, three different gate oxide processes were explored and compared. All MOS capacitors were fabricated on n-type GaN epilayers grown by MOCVD on sapphire substrates. C-V measurements were carried out on the three samples and their characteristics were compared. The very small interface-state density makes GaN MOSFETs a very good process choice for GaN MOSFETs and the trend of decreasing interface-state density deeper into the bandgap allows the demonstration of GaN inversion-mode MOSFETs. Both accumulation and inversion-mode MOSFETs were fabricated and characterized using OX3 process conditions. Field-effect mobilities were extracted on both circular and linear devices with different channel lengths. Mobilities in two perpendicular directions in (0001)-plane show similar values. Current collapse testing was also performed on our GaN MOSFETs and no current collapse was observed. In addition, an NMS inverter stage, utilizing an enhancement-mode MOSFET and a depletion-mode MOSFET has also been demonstrated and characterized.

Saturation Velocity Enhancement in Al2O2/AlGaN/GaN MOSHFETs: Peter Kordos; Roman Stoklas; Dagmar Gregusova; Jozef Novak; 1Academy of Sciences

Increases in the extrinsic transconductance (64%) and in the saturation drain current (40%) of the AlGaN/GaN MOSHFET with 4-mm-thick Al2O3 gate-oxide compared to the HFET were observed. An analysis of this effect yielded higher drift mobility in the MOSHFET than that in the HFET with the zero-bias values of 1950 and 1630 cm2/Vs, respectively. The extrinsic transconductance can be well fitted using measured data of roll-off and series resistance. The series resistance is found to be 10 and 5.8 Wmm for the HFET and MOSHFET, respectively. From the intrinsic transconductance evaluated using measured data of roll-off and series resistance. The series resistance is found to be 10 and 5.8 Wmm for the HFET. 

E-Devices: High Voltage Devices

Fabrication of Normally-Off Mode AlGaN/GaN HEMTs and Its Importance for GaN Electronics: Stephan Maroldt; Christian Haupt; Katja Tonisch; Oliver Ambacher; 1TU Ilmenau

Normally-off mode AlGaN/GaN HEMTs fabricated by a gate recess technology offer potentially a high transconductance due to a very thin AlGaN barrier thickness. Therefore a low maximum gate voltage is needed for turning this HEMT into an on-state, while simultaneously enabling operating at high output currents and high output voltage. This property is making them an ideal choice for high power electronics. In this work different technologies for obtaining normally-off behavior in AlGaN/GaN HEMTs are investigated and compared i.e. fluoride and ozone plasma based surface modification, a passivation layer as well as a low damage chlorine plasma gate recess etching. Besides being compatible with self aligned, short gate length fabrication using different passivation layers these technologies offer the possibility of integrating normally-off and normally-on mode HEMTs on one chip.

GaN High-Voltage Devices on Si: O. Schulz; 1; Nadia Heintel; J. Blaesing; A. Krich; T. Hempel; A. Diez; I. Daumiller; M. Kunze; J. Christen; C. Krosl; 1AZURRO Semiconductors AG; 2MicroGaN GmbH; 3Otto-von-Guericke-Universitaet Magdeburg

Having high breakdown field strengths the wide band-gap materials GaN and AlN are predestined for high voltage applications. However, the lack of homosubstrates and problems with the availability of large diameter substrates (SiC) and growth on them (sapphire) hampers a breakthrough of these materials due to high device cost. With silicon a low-cost large diameter material is available and growth on 150 mm diameter substrates has already demonstrated. The problem using Si is the comparably low high conductivity, low breakdown field strength and the difficulty to grow sufficiently thick and crack-free GaN layers to achieve high breakdown voltages. We have solved these problems and will present GaN-on-Si based FET devices for high-voltage switching applications above 1000 V.
Investigation on Conductivity at the GaN/AlN/SiC Substrate Interface for Vertical Nitride Power FETs: Iku Nakamota1; Funio Hasegawa1; Hideo Kawanishi1; 1Kogakuen University

Power FETs are the next promising application of AlGaN/GaN heterostructures. In order to reduce the device size and thermal conductivity, power nitride FETs should be a vertical structure on a conductive SiC or Si substrate. An AlN or/and AlN/GaN multi-buffer layer is inevitable to grow GaN on a SiC or Si substrate by MOVPE, therefore, current flow at the GaN/AlN/SiC interface is one of the important issues to be investigated. 17 to 350 nm AlN layers were grown on 800 nm AlGaN/Si substrate by MOVPE. Ni/AlN/n—epi-4H-SiC sample showed Schottky characteristics across 350 nm thick AlN sample, indicating that the AlN was not working as an insulator. On the other hand, Ni/AlN/GaN/n—epi-4H-SiC sample turned out MIS characteristics for the same AlN thickness. This difference can be explained by the heterovalent atomic structure at the interface between AlN(III-V) and SiC(IV-IV).

Switching Transients in AlGaN/GaN HEMTs Operated Under High Power: Pankaj Shah1; Ben Huebschman1; Edward Viveiros2; Khamouk Kingko1; Alfred Hung1; Ken Jones1; 1US Army Research Laboratory

Communication and Radar applications place great demands on high power, high frequency AlGaN/GaN HEMTs. Current transients originating from material properties can drain power from the source, degrade transmitted information, and contribute to lifetime reduction of a system. Drain-lag and gate-lag measurements are used to observe and interpret physically the transients during the HEMT operation and to develop models for use in ADS harmonic balance power amplifier simulation. Measurement results indicate that SiN passivated devices not exhibiting drain lag transients when operated under low stress will exhibit drain lag as the device temperature increases. Therefore, realistic operating conditions considering the modulation the device will experience in actual operation should be considered when evaluating a device. Measured results lead to AlGaN HEMT models based on a combination of HEMT and FET models available in ADS to accurately represent the physics in real devices.

E-Devices: Microwave Devices

0.15 μm Self-Aligned AlGaN/GaN High Electron Mobility Transistors: Vipin Kumar1; Dong-Hyun Kim1; Anirban Basu1; Ilesanmi Adesida1; 1University of Illinois

The high frequency response of AlGaN/GaN high electron mobility transistors (HEMTs) is still limited by the high access resistance. In order to reduce access resistance self-aligned devices with gate-length down to 0.15 μm have been fabricated on 6H-SiC substrates using a single step ohmic process. Our recently developed Mo/Al/Mo/Au-based ohmic contact requiring annealing temperatures between 500 and 600°C was utilized. Ohmic contact resistances between 0.3 - 0.5 ohm-mm have been achieved. These 0.15 μm devices exhibited maximum drain current density of 298 mA/mm at a gate bias of 0 V and a drain bias of 10 V. The knee voltage was less than 2 V showing the excellent nature of the ohmic contact. A peak extrinsic transconductance (gm) of 297 mS/mm was measured at Vgs = -2.6 V. Also, a unity gain cut-off frequency( fT ) of 98 GHz was measured on these devices.

Cryogenic Characteristics of Sub-100-nm-Gate AlGaN/GaN MIS-HEMTs: Akira Endoh1; Issei Watanabe1; Yoshimi Yamashita1; Takashi Mimura1; Toshiaki Matsui1; 1Rensselaer Polytechnic Institute

We fabricated AlGaN/GaN metal-insulator-semiconductor (MIS) high electron mobility transistors (HEMTs) using Si/SiO2/SiN triple-layer insulators, and measured their DC and RF characteristics at 300K and 16K. The maximum drain-sink current occurred at a drain-source voltage of 5 V and a gate-source voltage of 0 V increased from 11.3 μA/mm at 300 K to 1.075 μA/mm at 16 K. There was no current collapse at either 300 K or 16 K in the measured bias range. The cutoff frequency fT at 16 K was 18-26% greater than that at 300 K. At a gate length Lg of 45 nm, fT had a maximum value of 168 GHz at 16 K and 134 GHz at 300 K. The increase in fT may result from a reduction in access resistances and an increase in electron velocity.

DC and Microwave Performance of Recessed Gate III-N HETs with InGaN Etch-Stop Layer: Zhiqiang Yang1; Nezih Pala1; Jiayu Deng1; Xuhong Hu1; Alexei Kudymov1; Grigory Simin1; Jinwei Yang1; Remis Gaska2; Michael Shur1; 1Rensselaer Polytechnic Institute; 2Sensor Electronic Technology; 3University of South Carolina

Recessed and double recessed gate techniques have been employed in GaN HETF technology to increase the breakdown voltage without compromising the high frequency performance. However, conventional recessed-gate processes introduce damage and traps to the active region and are not able to selectively etch epitaxial layers. In this work, we present experimental studies of a novel AlGaN/GaN HETF structure with recessed gates fabricated by selective etching of textured AlGaN with etch-stop InGaN layers. Devices with 0.5 μm long recessed gate showed the breakdown voltage increase from 40 V to 130V. The threshold voltage was independent on drain bias, which indicates the reduced short channel effects. Cut-off frequency and maximum oscillation frequency were 29.4GHz and 39.7GHz, respectively. A non-field-plated passivated device delivered 6.5 W/mm power, with 45% PAE at 40V drain bias independent of UV illumination, indicating the high material quality and process maturity.

DC Performance of High-Power GaN FET Devices with Non-Alloyed Ohmic Contacts Fabricated by PAMBE-Based Selective-Area Growth: Huichan Seo1; Patrick Chapman1; Philip Kren1; Jung-Hee Lee1; Kyekyoon Kim1; 1University of Illinois at Urbana-Champaign; 2Kyungpook National University

We previously reported on the metal-semiconductor field-effect transistors (MESFETs) fabricated by selective-area growth (SAG) using plasma-assisted molecular beam epitaxy (PAMBE), which showed high peak drain current and transconductance. The SAG technique enabled selective growth of a heavily doped n−-GaN layer (1.0×1019 cm−3) solely for the source/drain regions, giving rise to an extremely low contact resistivity (1.8×10−5 Ω·cm2) for the MESFETs. In this study, we extend the same SAG technique to non-alloyed ohmic contacts. The specific contact resistances of Ti and Ti/Al with SAG were 3.5×10−4 and 5.1×10−4 Ω·cm2, respectively, demonstrating that the SAG technique can be gainfully employed to fabricate a variety of metal contacts. The DC performance of MESFETs and HEMTs will be investigated. The interface reaction between metal contact and GaN surface will be examined by X-ray photoemission spectroscopy (XPS) and secondary ion mass spectrometry (SIMS).

Effect of Image Charges in the Drain Delay of AlGaN/GaN HEMTs: Jinwook Chung1; Xu Zhao1; Tomas Palacios1; 1Massachusetts Institute of Technology

This work studies the origin of drain delay in AlGaN/GaN High Electron Mobility Transistors (HEMTs). This delay, equals to the transit time of a carrier through the depletion region at the drain side of the gate in a HEMT, accounts for almost 25% of the total delay in deep submicron devices, significantly limiting their maximum frequency performance. The drain delay is inversely proportional to ø, a parameter related to how injected electrons image at different metal contacts in a HEMT. ø can be engineered by artificially redistributing the image charges. By adding an additional metal contact in the HEMT structure (“mirror contact metal”), and varying its length and position, our simulation predicted at least a 2-fold improvement in the value of ø therefore significantly improving the high frequency performance and linearity of these devices. A new equivalent circuit model that takes into account all these effects will also be presented.

Effect of Silicon Nitride Passivation on Microwave Noise Characteristics in AlGaN/GaN HEMTs on Silicon Substrate: Zhihong Liu1; Subramaniam Arulmumar1; Chee How Lee1; Geok Ing Ng1; Tao Xu1; 1MMIC Design Center, Temasek Laboratories, Nanyang Technological University; 2School of Electrical and Electronic Engineering, Nanyang Technological University

Effect of silicon nitride (SiN) surface passivation by Plasma Enhanced Chemical Vapor Deposition (PECVD) on microwave noise characteristics of...
Technical Program

AlGaN/GaN High Electron Mobility Transistors (HEMTs) on high-resistivity (HR) silicon substrate has been investigated. After passivation, improved DC and microwave noise performance was observed. At 10 GHz, the minimum noise figure ($NF_{min}$) decreased by 25% (0.5 dB) and associate gain ($G_{a}$) increased by 10% (1.0dB) at Vd=12V and Id=50mA/mm. The decreased value of $NF_{min}$ and increased value of $G_{a}$ by surface passivation is due to the increase of extrinsic transconductance ($g_{m}$) and decrease of source resistance ($R_{s}$), which resulted from the increase of 2DEG sheet carrier density by suppression of surface traps. The value of $NF_{min}$ and $G_{a}$ for SiN passivated devices becomes less dependent on frequency, gate and drain bias, which shows the higher linearity and capability of being used in high drain voltage-based low-noise applications.

Field Engineering Using Drain Field Controlling Electrode for Ultra High Frequency GaN-Based Power HEMTs: Alexei Koudymov; Nezih Pala; Zijiang Yang; Xuhong Hu; Jianyu Deng; Jinwei Yang; Remis Gaska; Grigory Simin; Michael Shur; Rensselaer Polytechnic Institute; University of South Carolina

GaN HEMTs applications for ultra high frequency high power rely on their ability to operate under high bias. However, as the bias increases, the high-frequency performance of HEMT degrades due to high field region extension beyond the gate increasing the effective gate length. Therefore, the field engineering at the gate edges is very important for high frequency, high power applications. In this work, we present both experimental and numerical studies of GaN HEMT utilizing the Drain Field Controlling Electrode (DFCE) to reduce the electric field spread in the device gate-to-drain opening. The simulations are performed based on experimentally validated velocity-field dependence and, hence, are valid for gate length scaling down to deep submicron. It is shown that the use of the DFCE reduces the response delay due to high field region extension more than a factor of two allowing for ultra-high frequency operation at high drain bias.

Gate Recess Technology on AlGaN/GaN HFET with InGaN as Etch-Stop Layer: Xuhong Hu; Nezih Pala; Zijiang Yang; Jinwei Yang; Remis Gaska; Michael Shur; Rensselaer Polytechnic Institute; University of South Carolina

Combination of novel epitaxial growth and gate etching technology enabled us to successfully fabricate a high-power high-frequency recessed-gate AlGaN/GaN HFET. We incorporated InGaN layer in the MOCVD grown epi-structure as an etch-stop layer to precisely control the recess depth. For the RIE etching, the InGaN layer etch rate has been found to be us to be more than ten times lower than that of the AlGaN barrier layer. After the RIE etching, the InGaN layer is easily removed using wet chemical etching. We show that the quality of 2DEG at the AlGaN/GaN interface does not degrade during the gate recess process. Novel technology results in high device uniformity as confirmed by testing the maximum transconductance distribution over the 2 inches wafer. The devices with 0.5 μm long gate have the cutoff frequency close to 30 GHz and the breakdown voltage of 130 V without employing the field-plating technique.

High-Electron-Mobility AlGaN/GaN Heterostructures Grown on Si(001) by Molecular Beam Epitaxy for Microwave Application: Sylvain Joblot; Yvon Cordier; Fabrice Semond; Philippe Venneaux; Sebastien Chenot; Philippe Lorenzini; Marc Portail; Jean Massies; Souad Boulay; St. Touni; Arulkumaran Subramaniam; Liu Zhi Hong; Lee Chee How; Ng Geok Ing; Temasek Laboratories, Nanyang Technological University

We investigated for the first time, the effect of high temperature in the microwave power performance of AlGaN/GaN high-electron-mobility transistor (HEMTs) on high-resistivity Silicon (HR-Si) for different microwave frequencies of 3 GHz, 6 GHz and 8 GHz. Due to the smaller thermal conductivity of Si substrate, very little higher rate of decrease in device output power density ($P_{out}$) was observed. We can claim that the $P_{out}$ reduction with temperature from Si-based AlGaN/GaN HEMTs is almost similar to the $P_{out}$ reduction with temperature from Si-SiC substrate based AlGaN/GaN HEMTs. After high temperature stress, very small degradation was observed in the power performance of the device at 3 GHz. Moreover, the rate of decrease in $P_{out}$ with temperature is not much affected by measurement frequency. The AlGaN/GaN HEMTs on HR-Si can also be used for high-power and high-frequency applications at elevated temperatures.

Increase of Electron Velocity in GaN HEMTs by Electric Field Engineering: Xu Zhao; Jinwook Chung; Tomas Palacios; Massachusetts Institute of Technology

Electron velocity influences both the intrinsic delay and drain delay of AlGaN/GaN High Electron Mobility Transistors (HEMTs). The electron velocity in AlGaN/GaN structures reaches a maximum value of 2.5×10^7 cm/s at an electric field of 150 kV/cm. However, the electron velocity decreases very rapidly for electric field in excess of the optimal value. In standard GaN HEMT devices, the average electric field in the gate modulated region of the channel far exceeds the optimal value, which results in an effective electron velocity well below the peak electron velocity. In this paper, we proposed a new GaN HEMT structure with a recessed drain access region to tailor the electric field in the drain access region of these transistors. As a result of the smoothed electric field, our device simulations predict an increase of 50% in the effective electron velocity in the new devices.

Nitrile Based Nanotransistors as New Sources and Detectors of THz Radiations: Frederic Toppe; Bernard Gil; CNRS UMR-5650

The plasma waves in gates two-dimensional electron gas have a linear dispersion law, similar to the sound waves. The transistor channel is acting as a resonator cavity for the plasma waves, which can reach frequencies in the Terahertz (THz) range for a sufficiently short gate length Field Effect Transistors (FETs). THz emission and detection by nanometer III-V transistors have been recently reported. In this work we report on THz emission and detection by nanometer GaN/AlGaN HEMTs. In particular, we show that specific GaN properties allow to observe THz emission up to room temperature. Possible application of GaN/AlGaN transistors as new miniature THz sources will be discussed.

Phonon-Engineered Reduction of Intrinsic Delay in Nitride HEMTs for mm-Wave Operation: Devdip Jena; Jacob Khurgin; Yueji Ding; University of Notre Dame; John Hopkins University; Lehigh University

The RT of a nitride HEMT is limited by three delays: the charging delay for the source access region (~0.5ps), the drain delay (~0.5ps), and the intrinsic delay for electrons to traverse the channel (~1ps for a ~160 nm gate HEMT), indicating a saturation velocity of ~1.6×10^7 cm/s for a ~70 GHz RT device. By direct PL and time-dependent Raman measurements of III-V nitride HEMT structures, LO phonon lifetimes have been measured to be of the order of a few ps, and the high-field saturation velocity of electrons is shown to depend upon the carrier density in the 2DEG channel. A new theoretical model will be presented for high-speed transport properties that limit the intrinsic delay, and epitaxial solutions to the non-equilibrium phonon effect on HEMT speed will be presented. IEEE EDL 27, 877 (2006). APL, 89, 022103 (2006). APL, 89, 202117 (2006).
Temperature Effects on Short Gate-Length AlGaN/GaN HEMTs: Guang Chen; Dong Kim1; Vipan Kumar1; Ilesanmi Adesida1; University of Illinois at Urbana-Champaign.

AlGaN/GaN high electron mobility transistors (HEMTs) of two different gate-lengths were investigated at different temperatures before and after the passivation. Devices with gate-lengths of 100 nm and 250 nm were fabricated on MOCVD-grown AlGaN/GaN on SiC. The DC results show that the trapping effect is dependent on temperature. The trapped electrons were released at specific temperatures with resulting changes in device properties. Small-signal equivalent circuits are extracted for both devices at different temperatures. The drift velocity is calculated from the equivalent circuit. The 250 nm-device has a drift velocity about 60% lower than the drift velocity of 100 nm device. After passivation, IT decreased for both devices. From the small signal equivalent circuit analysis, this decrease is due to both increase in gate capacitance and decrease in transconductance.

E-Devices: Sensors and MEMS

GaN-Si-MEMS Structure Fabricated from Nano-Column GaN Quantum Well Crystal Grown on Si Substrate: Fang Ren Hu1; R. Ito1; Y. Zhao2; Kazuhiro Hane3; Tohoku University.

Nanocolumn InGaN/GaN multiple quantum-well crystals were deposited on Si (111) substrate. We propose a new light source device combined with MEMS (Micro-Electro-Mechanical Systems). The direction of the light beam emitted from an array of the light source can be changed by a light beam steering mechanism. From the Si substrate with GaN crystal, a micro-stage with comb actuators on which the InGaN/GaN QW film is patterned has also been fabricated. The proposed device is monolithically composed of the GaN LEDs and Si MEMS structures. Basic researches on the growth of GaN crystals on Si substrate were also carried out. Due to the column structure and the buffer layer, the crystals were relaxed enough to obtain strong photoluminescence.

Sensing and Current Transport Mechanisms of a High Performance Pd/AlGaN/GaN Schottky Diode Hydrogen Sensor: Masanichit Akazawa1; Hideki Hasegawa1; Hokkaido University.

AlGaN/GaN system is attractive for constructing integrated wireless hydrogen sensor chips for hydrogen monitoring. This paper investigates sensing and current transport mechanisms of a Pd/AlGaN/GaN Schottky diode hydrogen sensor. As reported recently, reverse leakage current was very low because the process is dissociative with a high energy barrier, some trade-off relation between the tilt and twist angle fluctuations as a function of the nitridation condition such as the nitridation time. In this paper, we discuss about such trade-off relation in the direct growth of InN on the nitridation sapphire substrates and also propose a simple model of initial nitridation process to explain it.

Cathodoluminescence Spectroscopy and Mapping of AlInN Films in the Mid-Composition Grown by RF-MBE: Yu Minura1; Sung-Bek Che1; Yoshihiro Ishitani1; Akihiko Yoshikawa1; Chiba University.

InN-based III-nitride semiconductors have attracted much attention as a promising material system for applications in infrared devices. However, AlInN ternary alloys in the mid-composition tend to have a poor crystallinity because of the phase separation arising from the large immiscibility between InN and AlN. We investigated on the detailed crystalline and optical properties of AlInN ternary alloys in the mid-composition grown by RF-MBE at the temperature in the range from 500 to 600°C using cathodoluminescence (CL) spectroscopy and mapping. The AlInN films grown at the temperature below 550°C have the CL spectra those peaks are lower in energy than their InN and AlN. We investigated on the detailed crystalline and optical properties of AlInN ternary alloys in the mid-composition grown by RF-MBE at the temperature in the range from 500 to 600°C using cathodoluminescence (CL) spectroscopy and mapping. The AlInN films grown at the temperature below 550°C have the CL spectra those peaks are lower in energy than their InN and AlN.

Growth of InAlN Thin Films on Si(111) Substrate with Ammonia-MBE: Shota Oishi; Seong-Woo Kim1; Toshimasa Suzuki1; Nippon Institute of Technology.

InAlN is a promising material not only for optoelectronic devices but also for new electronic devices such as InAlN/GaN-HFETs. InAlN thin films are usually grown with MOCVD or RF-MBE on a substrate. In this study, we grew InAlN thin films on Si(111) substrates with ammonia-MBE using HT-AlN buffer layer. Indium containing III-Nitride alloys require lower growth temperature and that is a disadvantage of ammonia-MBE to grow such materials. We varied growth temperature and In/Al flux ratio to control In mole fraction of InAlN. When the growth temperature was 550°C and flux of In and Al was 4.2E-8Tor and 2.0E-8Tor respectively, crack-free and 400nm-thick InAlN film with In composition of 12% was obtained. However, the InAlN film separated into two phases. Depth profile measurement of matrix elements will be achieved to determine the structure of this sample and to obtain single phase InAlN layer with ammonia-MBE.

Investigation into the Use of Molecular Hydrogen on the Growth of Gallium Nitride via Metal-Organic Molecular Beam Epitaxy: Daniel Billingsley; David Pritchett; Shawn Burnham; Walter Henderson; W. Doolittle; Georgia Institute of Technology.

Ammonia-based metal-organic molecular beam epitaxy (MOMBE) is a promising technique to exploit the benefits of molecular beam epitaxy (MBE) and metal-organic chemical vapor deposition (MOCVD). However, ammonia nitridation efficiency, as well as carbon contamination from metal-organic precursors must be improved. Molecular hydrogen (H2) was investigated as a simple technique to improve ammonia nitridation efficiency and to get carbon containing species. H2 pre-treatment of bare sapphire
before nitridation showed a 30% decrease in x-ray diffraction rocking curve (002) full-width at half maximum of the subsequent GaN with increasing pretreatment temperature, indicating improved crystalline quality. H2 introduction during GaN homoepitaxy on GaN templates resulted in an 87% reduction in carbon concentration and 20% increase in growth rate. The results demonstrate that the use of H2 during substrate pretreatment and growth can improve crystalline quality and growth rate while reducing carbon contamination.

**M-Plane III-Nitride Materials for Polarization Sensitive Devices Grown by PAMBE with Real Time Analysis by Spectroscopic Ellipsometry:** Pranob Morsa; Chris Boney; David Starikov; Abdelhak Bensaoula; 1University of Houston

In this paper we present a study of the growth of M-plane GaN, InGaN, and AlGaN epitaxial layers on LiAlO2 substrates by plasma assisted molecular beam epitaxy (PAMBE) coupled with in-situ spectroscopic ellipsometry (SE). Previous studies on M-plane materials have suggested that optimum growth conditions with respect to surface morphology are those giving rise to Ga1/3Al2/3 layers at low growth temperature. We study the growth nucleation of GaN on LiAlO2 substrates under Ga rich conditions and growth at Ga1/3Al2/3 layer coverage at low growth temperature. Previous studies on M-plane materials have suggested that optimum growth conditions with respect to surface morphology are those giving rise to Ga1/3Al2/3 layers at low growth temperature. We study the growth nucleation of GaN on LiAlO2 substrates under Ga rich conditions and growth at Ga1/3Al2/3 layer coverage at low growth temperature. Previous studies on M-plane materials have suggested that optimum growth conditions with respect to surface morphology are those giving rise to Ga1/3Al2/3 layers at low growth temperature. We study the growth nucleation of GaN on LiAlO2 substrates under Ga rich conditions and growth at Ga1/3Al2/3 layer coverage at low growth temperature.

**Epitaxy**

2D and 3D Growth Mode Coexistence during Initial Stages of GaN Nucleation on AlN(0001) Surface in Ammonia MBE: Andrey Nikitin; Vladimir Mansurov; Yuriy Galitsyn; Konstantin Zhuravlev; Pierre Trone; 2Laboratoire d’Optique Physique, Ecole Superieure de Physique et Chimie Industrielles

The purposes of the present work are investigations of relations between 2D and 3D nucleation and subsequent growth of GaN on (0001) AlN surface in wide range of the growth parameters. In situ behavior of integer and fractional order 2D diffraction streaks as well as transmission 3D Bragg spots was experimentally investigated by RHEED. The coexistence of 2D streaks intensity oscillations and 3D spots intensity increasing was revealed. Usually abrupt 2D-3D transition is observed in this system that is connected with Stranski-Krstanov growth mode. In contrast, in our experiment we observed continuous increasing of intensity Bragg spots resulted from 3D GaN islands. The Bragg spots width and in-plane lattice parameter were also changed permanently. This experimental facts point to heterogeneous 3D nucleation of GaN on AlN surface.

The exponential increasing of 3D GaN islands density as function of time was revealed. Experimental results are discussed in terms of scaling theory.

**Impurity Incorporation in N-Face GaN by Plasma-Assisted Molecular Beam Epitaxy:** Mau Hua Wong; Tom Mates; James Speck; Umesh Mishra; 1University of California Santa Barbara

Unintentional impurity incorporation in N-face GaN grown on C-face SiC by plasma-assisted MBE was studied. Direct nucleation of GaN on SiC resulted in high Si and C incorporation from the substrate, with the Si causing undesirable conduction in HEMT buffers. A 50nm N-rich AlN nucleation was sufficient in suppressing Si and C concentration to 10^10 cm^{-2} in the subsequent GaN layer without significant impact to structural quality. Such nucleation scheme, together with two-step GaN to reduce threading dislocation density, offers high quality insulating materials for N-face electronics. The growth and transport of Si-doped and Mg-doped GaN on these buffers were studied. Room temperature electron mobility varied with [Si], with peak value of 355 cm^{2}Vs at [Si]=1x10^{16} cm^{-3}. Mg incorporation is dependent on III/V ratio and growth temperature. Room temperature hole mobility of 6.5 cm^{2}Vs was measured at [Mg]=1.2x10^{19} cm^{-3}. This work provides useful information for engineering N-face devices.

**Influence of the Mn Compositional Distribution on the Magnetic Order in Diluted GaMnN Layers:** Dong-Du Mai; Tore Niermann; Jan Zenneck; Amilcar Bedoya Pinto; Joerg Malindretos; Michael Seibt; Angela Rizzi; 1Georg-August-Universitaet Goettingen

GaMnN is a prototypical GaN-based DMS and its potential as a room temperature ferromagnetic material is still a controversial question to be answered. Diluted GaMnN layers with Mn concentrations up to several percent have been grown by plasma-assisted MBE on MOVPE-GaN/Al2O3 substrates under various growth conditions. None of the samples reported here show second phase precipitates in XRD or in the TEM analysis. However different composition distributions have been evidenced by EDX during the scanning TEM analysis. GaMnN grown at Tc=650°C exhibits extended structural defects and strong compositional inhomogeneity. This could be indicative of spinodal decomposition due to local strain. Samples grown at Tc=775°C with a Mn concentration below the yield of second phase formation show a homogeneous Mn distribution in the layer. The magnetic properties are found to vary from spin glass to ferromagnetic behaviour at room temperature in different samples.
InGaN Compositional Control by Ultraviolet Photoc excitation during NH3-Based MOMBE – A Pathway to 3D Epitaxy: David Priecht1; Walter Henderson2; Daniel Billingsley3; William Doolittle4; *Georgia Institute of Technology

Novel device concepts integrating features such as low-dimensionality and lateral bandgap energy modulation are complicated by expensive lithography, etching, and regrowth sequences. Metal organic molecular beam epitaxy (MOMBE) is a good candidate for in-situ patterned epitaxy of such structures due to a high vacuum environment and sensitive growth mechanism. The sensitive MOMBE growth pathways may be carefully manipulated for surface selective epitaxy. Despite successful arsenic, phosphide, and antimonide based structures grown by MOMBE with patterned dielectric masks, NH3-based MOMBE of nitrides has received little attention. Herein, we report the first InGaN films by NH3-based MOMBE. We identify a III-alkyl desorption phenomena inversely related to the resultant indium mole fraction. Moreover, we report significant InGaN alloy compositional variation using in-situ micromirror-patterned ultraviolet (UV) photoc excitation. Coupled with reported UV photoexcitation effects on GaN carbon doping, the technique shows promise for dynamic manipulation of nitride growth useful for complex, 3D device structures.

Nitrides on a-Plane LiAlO2: Li-Wei Tu1; H. M. Huang2; M. Z. Hsu3; L. K. Wang4; Y. L. Teng5; M. C. Chou6; Q. Y. Chen7; W. K. Chu8; *National Sun Yat-Sen University; *University of Houston

Gamma-phase lithium aluminate (LiAlO 2) single crystal is grown by Czochralski pulling method and a-plane LiAlO 2 (LAO) is chosen as the substrate for subsequent nitride epilayer growth. The growth conditions for the high quality a-plane LiAlO 2 substrates are discussed. The hexagonal GaN in the [10-10] direction is successfully grown directly on the LAO substrate without buffer layer. Crystal quality and properties are analyzed through a series of measurements, including reflection high-energy electron diffraction (RHEED), field-emission electron microscopy (FESEM), cathodoluminescence (CL), photoluminescence (PL), x-ray diffraction (XRD), Raman spectroscopy, etc. Nanostructures and others are also explored on top of the non-polar a-plane GaN layer. Electron backscatter diffraction (EBSD) is performed on the samples to determine the nanocrystal orientation and quality.

Non-Polar a-Plane GaN Grown on r-Plane Sapphire by Ammonia Source Molecular Beam Epitaxy: Tsuchai Zhu1; Amelie Dussaigne2; Claire Pinquier1; Denis Martin1; Nicolas Grandjean1; *Ecole Polytechnique Fédérale de Lausanne

Thin a-plane GaN layers are grown on r-plane sapphire substrates by ammonia source molecular beam epitaxy (MBE). Optical properties are investigated by low temperature (LT) photoluminescence (PL). The LT PL spectra are dominated by near band-edge emission at ~3.47 eV, with full width at half maximum ≤ 20 meV, indicating the good quality of the epilayers. Both basal stacking faults related emission peak at 3.42 eV and defects-related emission peak at 3.30 eV are observed, with a much lower intensity. Besides, the surface morphology and structural properties of MBE-grown epilayers are characterized by atomic force microscopy and high resolution X-ray diffraction, respectively. Furthermore, GaN/AlxGa1-xN single quantum well (well width ≈ 8 nm) grown on this template by MBE. Its LT PL emission peak at ~3.51 eV confirms the absence of internal electric field.

Plasma Assisted Molecular Beam Epitaxy of AlGaN/GaN High Electron Mobility Transistors: Rolf Aidum1; Lutz Kirste1; Michael Kunzer1; Stefan Müller2; Patrick Walter3; *Fraunhofer IAF

We report on the plasma-assisted molecular beam epitaxy of AlGaN/ GaN high electron mobility transistors (HEMTS). Growth was performed on MOVCVD grown GaN Templates and SiC wafers with 3° diameter. In a detailed study of GaN growth conditions the growth rate was varied between 0.18 and 0.5 μm/h. Under optimised conditions, the surface root mean square roughness was less than 0.6nm. Low temperature PL measurements in the range 1.9 to 3.8 eV showed only the exciton-emission with a FWHM of 12meV. AlGaN-HEMT structures exhibited room temperature Hall mobilities in excess of 1600 cm²/Vs and sheet electron concentration of 7 x 1012/cm². We will present buffer leakage data, studied by measurement of drain source IV characteristics, as well as DC, small signal and RF measurements on HEMTs.

Properties of Fe Doped GaN Films Prepared by Molecular Beam Epitaxy: Alexander Polyakov1; Nikolai Smirnov1; Anatoly Govorkov2; Alexander Markov3; Tatyana Yugoava4; Elena Petrova5; Amir Dabiran6; Andrew Wowchak7; Andrei Osinsky8; Peter Chow9; Stephen Pearton10; *Institute of Rare Metals; *SVTA Associates, Inc.; *University of Florida

Electrical properties were studied for MBE GaN films grown with various Fe concentrations, together with the results of electrical characterization of lightly doped n-GaN films and HEMT structures prepared on such buffers. SIMS profiling shows that, in contrast MOVCVD, there are no long tails of Fe concentration extending into the undoped portions of the films. The buffers are semi-insulating, with the Fermi level pinned near Ec-0.5 eV. In agreement with SIMS data, we did not detect the presence of Fe related centers in the n-type portions of the films in the concentration exceeding some 1014 cm-3. HEMTs prepared on such buffers showed good pinch-off in I-V and C-V characteristics, good interdevice insulation, and high 2DEG mobility and density. All that suggests Fe doped MBE grown buffers as a good option for preparation of HEMT structures. Detailed studies point to the optimal range of Fe source temperatures for transistor applications.

RF-MBE Growth of Cubic InN Films on YSZ(001) Vicinal Substrates: Tetsuya Nakamura1; Takahiro Katakawa2; Ryuu Katayama3; Kentaro Onabe4; *University of Tokyo

The YSZ(001) vicinal substrates were adopted to the growth of cubic-phase InN films in an attempt to improve the cubic-phase purity in the film. The YSZ substrate has the advantages of the small lattice-mismatch (3%) to InN and the atomically flat surface with a step-and-terraced structure obtained by annealing. The hexagonal-phase incorporation (HPI) is much reduced by the growth on such a well-defined surface as shown before. In this study, the InN films were grown by RF-MBE on the YSZ(001) just 1° misoriented (toward [110]°) substrates annealed at 1250°C in air. From an analysis of the X-ray diffraction reciprocal space mapping, it is known that the HPI ratio has decreased from 16.3% to 11.7% by using the vicinal substrate, and that the hexagonal phase is generated predominantly through the stacking faults on the c-InN(111) facets which are inclined to the upward direction of the atomic steps.

Strain Control in AlGaN/GaN HEMT Grown on SiC by Ammonia MBE: Huipeng Tang1; Stephen Rolfe1; Jean-Marc Baribeau1; Jennifer Bardwell1; *National Research Council Canada

AlGaN/GaN HEMT structures grown by ammonia MBE on SiC substrates exhibit a biaxial tensile strain due to a large decrease of the thermal expansion coefficients of the GaN material and SiC. The thermally induced tensile strain after cooling down from a growth temperature of about 900°C is in the order of 0.1%. This level of tensile strain is significant enough to cause cracking of the HEMT structure either immediately after growth or during subsequent processing steps. Here we report results of control of lattice strain during growth so that built-in compressive lattice strain offsets part of the tensile thermal strain. The role of the AlN buffer layer and the effect of its thickness were investigated. Using two AlN interlayers within the semi-insulating (carbon-doped) GaN layer was found to effectively reduce the tensile strain. The strain engineered HEMT structures were stable in all device processing procedures including the surface passivation.

Heterostructures

AlGaN-Based Heterostructures Grown on 4 Inch Si(111) by MOVPE: Kai Cheng1; Maarten Leys2; Joff Derluyn3; Krishnan Balachander4; Stefan Degroote5; Marianne Germain6; Gustaaf Borghs7; *IMEC

AlGaN is an important material for ultra-violet light emitters, photo detectors and high breakdown switching devices. In this work, crack-free...
Technical Program

AlGaN$_x$N (5% < x < 55%) layers up to 1.5 μm have been grown on 4 inch Si(111) using an AlN/AlGaN$_x$N (y > 70%) template. The structural quality of AlGaN layers is comparable to that of GaN layers grown on silicon(111). For Al$_{0.5}$Ga$_{0.5}$N, the FWHM of XRD (0002) and (-1102) o-scans are around 650 and 1200 arc sec respectively. Based on this high quality AlGaN buffer, a double heterostructure (DH) FET was demonstrated. The sheet resistance of DH-FET is 274 ± 4.7 Ω/;/ and the uniformity value of 1.7% is also excellent. Some of the wafers have been processed. Devices with a gate length of 2μm show current density of 500 mA/mm and transconductance of more than 200 mS/mm.

Characterization of Mg-Doped AlInN Grown by Metalorganic Vapor Phase Epitaxy: Yan-Kuin Su$^a$; An-Tong Cheng$^b$; Wei-Chi Lai$^c$; $^a$Advanced Optoelectronic Technology Center, Institute of Microelectronics and Department of Electrical Engineering, National Cheng Kung University; $^b$Institute of Electro-Optical Science and Engineering, National Cheng Kung University

We report on the growth of undoped and Mg-doped AlInN by metalorganic vapor phase epitaxy. The indium content and the FWHM of undoped AlInN layer were 20.9% and 219.6 arcsec, respectively, from HRXRD measurement. It was also observed that an additional satellite peak was formed near the AlInN peak after introducing the Mg dopant. The sheet hole concentration of 4.73×10$^{12}$ cm$^{-2}$ was achieved after performing the thermal annealing. As the flow rate of CP$_2$Mg source was increased, we found that both the satellite peak and the AlInN peak shifted toward higher angles. However, higher CP$_2$Mg flow rate would not only decrease the conductivity of AlInN layer due to the higher Al content shown in HRXRD spectrum but increase the surface roughness. Therefore, these results suggest that p-type AlInN cladding layer nearby lattice-matched to GaN will be realized with lower CP$_2$Mg flow rate for optical device applications.

Comparative Studies of InGaN Multiple Quantum Wells Grown on Porous and Non-Porous GaN Layers by Metal-Organic Chemical Vapor Deposition: Yong-Hwan Kim$^a$; Seol Back$^b$; Ho-Sang Kwack$^c$; Ki-Yon Park$^d$; Yong-Hoon Cho$^e$; $^a$Chungbuk National University

We have investigated the structural and optical properties of InGaN multiple quantum wells (MQWs) grown on porous and non-porous GaN layers by metal organic chemical vapor deposition (MOCVD). A 2 μm-thick undoped GaN layer was grown on sapphire substrate by MOCVD technique, and then chemically etched to form porous GaN layer. After the fabrication of the porous GaN layer, an InGaN MQW light emitting diode (LED) structure was grown on top of this porous GaN structure by MOCVD (sample A). For comparison, the same InGaN MQWs LED structure was grown on an un-etched (non-porous) GaN layer (sample B). The PL peak wavelength of sample B was observed to be about 436 nm, while a 32-nm blueshift was observed for sample A, which can be attributed to the change in stress and related internal field effect. Detailed comparison of the structural and optical properties for these samples will be given.

Demonstration of GaN/InGaN Light Emitting Diodes on (100) β-Ga2O3 Substrates by Metalorganic Chemical Vapor Deposition: ZiLi Xie$^a$; Dong Hyuk Kim$^b$; Go Eun Lee$^c$; Yong Seon Jeon$^d$; Euijoon Yoon$^e$; Do-Young Park$^f$; Yong-Hwan Cho$^g$; $^a$3Ioffe Physico-Technical Institute; $^b$National Central University; $^c$3Sogang University; $^d$EpiValley Company, Ltd.

The reduction of H radicals in growth ambient will be a useful method for as-grown p-type GaN because the main origin of Mg passivation in p-type GaN is the H radical from NH$_3$. Observation of three absorption peaks related to CHn complexes in FT-IR spectra suggests hydrogen trapping at carbon impurities. DMHy can reduce H radical concentration in growth ambient by the formation of CHn complexes, resulting in p-type conductivity of as-grown Mg-doped GaN.

Effect of Dimethylenehydrazine in p-Type Conductivity of as-Grown Mg-Doped GaN: Yong-Hwan Cho$^a$; Dong Hyuk Kim$^b$; Go Eun Lee$^c$; Yong Seon Jeon$^d$; Euijoon Yoon$^e$; Do-Young Park$^f$; Yong-Hwan Cho$^g$; $^a$3Ioffe Physico-Technical Institute; $^b$National Central University; $^c$3Sogang University; $^d$EpiValley Company, Ltd.

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Effect of Metallic Surface Coverage on Material Quality in III-Nitride MOVPE: Alexey Kondratev$^a$; Roman Talalaev$^b$; Alexander Segal$^c$; Eugene Yakovlev$^d$; Wsevolod Lundin$^e$; Evgeny Zavarin$^f$; Mikhail Sinitzin$^g$; Andrew Tsatsulinov$^h$; $^a$Soft-Impact; $^b$Semiconductor Technology Research GmbH; $^c$Ioffe Physico-Technical Institute

Pinsholes or V-like defects are the well known type of defects, characteristic for nitride growth by MOVPE. This paper reports on the studies of correlation between defect appearance and MOVPE growth conditions and discusses the ways to improve the material quality. Decrease of ammonia flow at constant total flow during MOVPE of GaN in hydrogen-ammonia atmosphere at moderate temperatures (750-900°C), has revealed the overgrowth of pinsholes up to their almost complete disappearance. The same effect was observed at the addition of a certain amount of TMG and was accompanied by very small incorporation of indium into the crystal. In both cases the improvement in morphology was associated with accumulation of metallic (Ga and In, respectively) atoms in the adsorption layer at the growing surface. This conclusion was supported by surface kinetics model computations. The model suggests the possible strategies for growth of the pinhole-free layers for various device structures.
Effects of Growth Temperature and Reactor Pressure on the InGaN Films Grown by Metalorganic Chemical Vapor Deposition: Xian Suet; 1Institute of Semiconductors, Chinese Academy of Sciences
InGaN films have been grown on GaN template by metalorganic chemical vapor deposition with the condition of varied growth temperature and reactor pressure. The In composition is determined by θω-2θ scan of Double-Crystal X-ray Diffraction (DC-XRD) and room-temperature photoluminescence (PL) measurements. It was found that the In composition increases with the reactor pressure from 100Torr to 200Torr, and slightly decreases as it increases from 200Torr to 400Torr. The growth rate and In composition of InGaN films increase with decreasing growth temperature. The potential reason lies in that InN is more stable at lower temperature. Crystal quality of InGaN films degrades with the increase of In content indicated by the full width at half maximum of θω scan of XRD. However, extremely low growth temperature and high In/Ga ratio lead to the appearance of In droplets on the surface.

Epitaxial Lateral Overgrowth of GaN on 4” Si(111) by MOVPE: Kai Cheng; Vasyi Motsnyi; Maarten Leys; Stefan Degroote; Bram Sijmus; Marianne Germain; Gustaaf Borghs; 1IMEC
Epitaxial Lateral Overgrowth (ELOG) of GaN on 4” silicon (111) substrates by MOVPE was investigated in this study. ELOG was performed on a GaN template with a couple of AlGaN intermediate layers (IL) on an AlN nucleation layer. The AlGaN ILs supply compressive stress to the top GaN template and thereafter to the ELOG layer. Consequently, layer cracking is minimized. Two masks were used in this work: a 2” wagon wheel mask and a 4” mask with parallel stripes of various template and thereafter to the ELOG layer. Consequently, layer cracking is minimized. Growth experiments as manifested by high AlN growth rate, 2 m/h, and strong UV light emission at room temperature.

GaN Growth on Silane Exposed AlN Seed Layers: Francisco Ruiz; Oscar Contreras; Armin Dadgar; Aloys Krost; 1 Centro de Investigación Científica y de Educación Superior de Ensenada; 2 Centro de Ciencias de la Materia Condensada, UNAM; Otto-von-Guericke Universität Magdeburg
The microstructure and surface morphology of GaN films grown on AlN seed layers exposed to silane (SiH₄) flow, has been studied by AFM and TEM. The AlN seed layer surface was treated at different SiH₄ exposure times before the growth of the GaN film by MOCVD. Radical changes are observed on the surface morphology of the GaN films as a function of the SiH₄ treatment. A pit density reduction is observed at the surface of GaN as a function of the SiH₄ exposure time. The surface roughness is minimized for an optimal time of 75 to 90 sec of SiH₄ exposure and a step-flow growth mode is observed at this condition. A cross-sectional microstructural analysis reveals a conglomeration of threading dislocation right above the AlN seed layer, which reduces the dislocation density at the surface resulting in an improvement of the GaN surface quality.

Growth Characteristics of AlGaN/GaN HEMTs on Patterned Si(111) by MOCVD: Hong Wang; Congshun Wang; Kevin Chen; Kei May Lau; 1 Photonics Technology Center, Electronics and Computer Engineering Department, HongKong University of Science and Technology; 2 Electronics and Computer Engineering Department, HongKong University of Science and Technology
Growth characteristics of AlGaN/GaN HEMT structures on patterned Si(111) substrates are reported. The patterns on the Si substrates were fabricated by SiO₂ or Si N masks and wet etching. Growth experiments were carried out in a multi-wafer MOCVD system on unpatterned, patterned without mask, and patterned with mask Si wafers. Double AlN interlayers grown at high temperature were employed to release the tensile stress from the large mismatch in the lattice constants and thermal expansion coefficients. Before achieving optimized growth conditions, more cracking lines were observed on patterns along the [1-100] orientation than along the [11-20] orientation, resulted from more stable GaN (1-100) facets than GaN (11-20) facets. It is suggested that long patterns should be made along the [11-20] orientation. Micro-Raman measurements showed that Raman shifts at the concave corners are bigger than that at the convex corner, indicating the larger stress at the concave corners.

Growth of Nonpolar GaN Epitaxial Film on a Latticed-Matched γ-LiAlO₂ Substrate by Chemical Vapor Deposition: Chenlong Chen; Mitch M.C. Chou; Da-Ren Hang; Cheng-Hong Way; Jih-Jen Wu; 1 National Sun Yat-Sen University; 2 National Cheng Kung University
In this report, a simple chemical vapor deposition approach to the growth of nonpolar GaN with [10-10] orientation on a (100) γ-LiAlO₂ substrate was presented. The orientation of GaN film is identified as [10-10] or m-plane by X-ray diffraction pattern (XRD). The surface morphologies of GaN film were investigated by scanning electron microscopy (SEM). The SEM image shows a high density of well-aligned GaN islands with rectangular structure. GaN hexagons lied down on the surface of LiAlO₂ substrate. The orientation of GaN hexagons is the same as the assumption of lattice match. The SEM image also showed that GaN has a higher growth rate in lateral (0001) direction which is parallel to LiAlO₂ substrate than (10-10) growth direction. Photoluminescence (PL) characteristics of the GaN films show a strong UV light emission at room temperature.

Heteropitaxial Growth of High Quality GaN Thin Films on Si Substrates Coated with Self-Assembled Submicron Silicon Balls: Sung Jin An; Young Joon Hong; Gyu-Chul Yi; Yong-Jin Kim; Dong Kun Lee; 1 POSTECH; 2 LG Siltron
A simple maskless overgrowth technique without either lithography or interruption can simplify the growth process, which is very helpful for high yield and low cost device fabrications. Here, we present a maskless heteropitaxial GaN growth on a Si substrate with a self-assembled submicron silicon ball layer (SBS). Monodispersed submicron-size silicon balls were employed as an intermediate layer for heteropitaxial growth of GaN. The GaN surfaces were fairly flat, and no pits or cracks were observed. The FWHM value of rocking curve was 0.18°, much smaller than that of GaN epilayer on bare Si substrates, 0.30°. Furthermore, TEM and AFM revealed many enhanced structural characteristics and improved crystallinity for the GaN films on SBS substrates. In particular, for the regions on or near the silica balls, no threading dislocations were observed and the total number of dislocations of the GaN on SBS substrate was smaller than 10⁶ cm⁻².

High Efficiency Epitaxial Growth by Hot-Wall MOCVD in Nitrogen: From Experiment and Theory: Anelia Kakanakova; 1 Linköping University
We show the beneficial effect of nitrogen on the GaN MOCVD growth process as manifested by high AlN growth rate, 2 μm/h, and strong cathodoluminescence AlN near band edge emission when the AlN growth was done in nitrogen carrier gas only. Comparison is done to the properties of the AlN layers when grown in hydrogen only and in mixture of hydrogen and nitrogen. The direct participation of nitrogen in the modification of gas-phase chemistry is studied via Density Functional Theory calculations by considering the stability of reaction species like adducts, corresponding transition states for methane elimination and adduct-derived chain complexes, when exposed to an ambient of hydrogen or nitrogen molecules. The growth, including on 2 inch SiC wafers, is performed in hot-wall MOCVD reactor at temperatures higher than 1100° C in the view of the ever anticipated understanding that elevated temperatures during AlN epitaxy promote better crystal quality.

Highly Uniform Hot-Wall MOCVD Growth of High-Quality AlGaN/GaN HEMT-Structures on 100 mm Semi-Insulating 4H-SiC Substrates: Erik Janczak; Anders Lundskog; Urban Forsberg; Anelia Kakanakova-Georgieva; Ivan Ivanov; 1 Linköping University
We have grown an AlGaN/GaN HEMT structure on a semi-insulating 100 mm 4H-SiC substrate in a hot-wall MOCVD reactor with rotation of the wafer during growth. The epi thickness is highly uniform with an average of 1.77 μm and a nonuniformity (sigma/average) of 2.8 %. The sheet resistance is highly uniform with a very low average of 268 Ω and a nonuniformity (sigma/average) of 2.1 %. The results from mercury probe CV-measurements are: Sheet carrier density 9.9E12 cm⁻², V( pinch-off) = - 5.3 V, thickness of (AlGaN + AlN) = 25 nm, no electrons in the GaN layer. From the measured
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Improved Surface Morphology of Flow-Modulated MOVPE Grown AlN on Sapphire Using Thin Medium-Temperature AlN Buffer Layer: Dabing Li; Masakazu Aoki; Hitode Miyake; Kazumasa Hiramatou; ‘Mie University

High-temperature (HT) AlN films were grown on (0001) sapphire by low-pressure flow-modulated (FM) MOVPE with and without inserting a thin medium-temperature (MT) AlN layer. The AFM and SEM measurements indicated that the thin MT-AlN layer had a strong influence on the surface morphology of the HT-AlN films. The surface morphology became quite smooth by inserting the thin MT-AlN layer and surface RMS roughness values were 0.84nm and 13.4nm for the HT-AlN films with and without the thin MT-AlN buffer layer, respectively. By etching the samples in aqueous KOH solution, it was found that the polarity of AlN films was different. The full width at half maximum values of (0002) and (10-12) for HT-AlN without the MT-AlN layer are 90arcsec and 1080arcsec and for HT-AlN with the MT-AlN layer are 65arcsec and 1512arcsec. The mechanism for the origin of the different polarity of HT-AlN with and without the thin MT-AlN layer was discussed in detail.

Isotropic Coalescence Behaviours of GaN Islands Grown by Metalorganic Chemical Vapor Deposition: Soo-Jin Chua; Hai Long Zhou; D.J. Stolovitz; Dan Xu Du; 1stitute of Materials Research and Engineering; ‘National University of Singapore; ‘Yeshiva University; ‘Princeton University

In Epitaxial Layer Overgrowth (ELO) technology, GaN is grown inside the stripe window of a SiO2 mask and then laterally over the mask to eventually merge and form a uniform thin film. The merging behaviours of GaN islands along different directions can influence the strain and bending of dislocations. GaN islands which merge along the direction have two parallel sides of the hexagonal islands aligned parallel whereas those aligned in the direction have there tips pointed towards one another. Growth along is found to be faster than along by a ratio of 1:0.85. After merging, the island shows different shapes which affect the strain within the islands. After the growth of the stripes to form triangular ridges, the facets are formed on stripes aligned along while the facets are formed on stripes aligned along. Defects are observed on the facets but not on the facets.

Low Temperature Growth of Nitride Films by Near-Atmospheric Plasma-Assisted Chemical Vapor Deposition: Takahiro Nagata; Yoshiki Sakuma; Junichihiro Azama; Tsuyoshi Uehara; Syunsuke Kunugi; Toyohiro Chikyow; ‘National Institute for Materials Science; ‘Sekisui Chemical Company, Ltd.

We have demonstrated the growth of GaN film by near-atmospheric plasma-assisted chemical vapor deposition for the first time. Pure nitrogen plasma can be generated stably using an alternating pulsed voltage system that applies an alternating pulsed voltage between two parallel plate electrodes. The excited nitrogen species correspond to the nitrogen second positive system. Using this plasma as a nitrogen source, metalorganic chemical vapor deposition of GaN thin films were carried out under a nitrogen partial pressure of 40 kPa. GaN thin films epitaxially at 400°C, and crystalized at as low as 150°C on (0001) sapphire substrate. From the results obtained, we found that the process using near-atmospheric plasma-assisted chemical vapor deposition has major potential for use in nitride film fabrication under high-nitrogen partial pressure and at low temperatures. In the presentation, effects of metal precursors and process gas will be discussed in detail.

Mechanisms of AlInN Growth by MOVPE: Modeling and Experimental Study: Eugene Yakovlev; Anna Lobanova; Roman Talaeva; Ian Watson; Katharine Lorenz; E. Alves; ‘Soft-Impact, Ltd.; ‘Semiconductor Technology Research GmbH; ‘Institute of Photonics, SUPA, University of Strathclyde; ‘Instituto Tecnologico e Nuclear

The scope for lattice matching between AlInN alloys and GaN attracts much interest for fabrication of stress-free multilayer structures for photonic and electronic applications. In this paper, the efficiency of indium incorporation into AlInN has been studied by reactor-scale computational modeling, and experimentally, for epilayers grown on GaN/sapphire substrates in an Aixtron AIX 200/4 RF-S reactor. The AlInN growth setpoint temperature ranged from 760 to 840°C, and layer compositions were measured using Rutherford backscattering. It was found that the indium content reduces with temperature, and that compositional grading occurred at the lowest growth temperature studied. Numerical modeling reproduces the experimental compositional data well, so it can be applied for further analysis of mechanisms governing AlInN deposition. For this purpose, the effects of different operating parameters on the growth rate and InN content have been modeled. From the model predictions, conditions providing a particular target layer composition can be proposed.

MOCDV Growth and Characterization of UV-LEDs Grown Using a Thin GaN Interlayer on a High Temperature AlN Buffer: Tao Wang; ‘University of Sheffield

It is a great challenge to achieve high-quality AlN layer for growth of UV emitters on sapphire. Recently, we developed a so-called GaN interlayer approach, i.e., ~20nm GaN layer is deposited on the AlN buffer prior to growth of any further structure. TEM confirmed that the dislocation density of the overlying structure has been significantly reduced. Both 340 nm and 315 nm UV emitters with improved performances have been obtained. Compared to the similar structure but without the interlayer, the EL intensity of the 340 nm LED is significantly increased by a factor of 3, and the bias voltage at 20 mA was decreased from 6.5 to 5.1V and the leakage current at a reversed bias of 10 V was reduced by more than one order magnitude. The 315 nm LED showed a strong peak at 315 nm, as expected. Further pushing the UV-LEDs toward shorter wavelengths is on-going.

MOCDV Growth of Hexagonal Nitridge on Si(100): Qian Sun; Soon-Yong Kwon; Jung Han; ‘Yale University

Recently two research groups have demonstrated hexagonal GaN-based LED and HEMT on offset Si(100). The GaN material quality on Si(100) is at present much worse than that of GaN on sapphire or Si(111). In this paper we investigated the growth of AlN and Al0.13Ga0.87N on 4-deg. offset Si(100) to achieve single crystalline hexagonal phase. It is found that an optimum Al-pre-deposition and a high growth temperature play significant roles in the morphological and structural quality. V/III ratio during subsequent AlGaN growth is crucial in determining in-plane alignment. Al0.13Ga0.87N grown under a low V/III ratio shows a very rough surface with many misaligned grain boundaries prohibiting coalescence and gives only a broad deep level emission around 375 nm. But the room temperature photoluminescence of smooth Al0.13Ga0.87N epilayer obtained under a high V/III condition presents a strong near band-edge emission around 334 nm. Evolution of heteronucleation and AlGaN heterostructures will be reported.

MOCDV Growth of InGaN/GaN MQW on ELOG GaN Facets for Monolithnic White Emission: Jin-Woo Ju; Lee-Woon Jang; Seung-Jae Lee; Jong Hyoe Baek; In-Hwan Lee; ‘Chonbuk National University; ‘Korea Photonics Technology Institute

We have investigated multiwavelength emitting InGaN/GaN quantum wells (QWs) formed on V-shaped GaN (1-101) microfacet. After a metalorganic chemical vapor deposition of 2μm thick GaN, SiO2 mask stripes were formed along GaN <11-20> direction by a conventional photolithography.

Marked Improvements in Electrical and Optical Properties for MOVPE InN Annealed at a Low Temperature (~300°C) in O2 Atmosphere: Yasuhiko Nagaia; Ken-ichi Sugita; Akihiro Hashimoto 1; Akio Yamamoto1; ‘National Institute for Materials Science; ‘1Mie University

We have found that electrical and optical properties for MOVPE InN are markedly improved when the grown samples are annealed in the air at a low temperature around 300°C. The InN films used in this study are grown on (0001) sapphire substrates using an atmospheric-pressure MOVPE system with a horizontal reactor. For the sample annealed at 300°C for 5 h in the air, the carrier concentration is reduced to 5 × 1018 cm-3 from 2 × 1019 cm-3 for an as-grown sample. The reduction in carrier concentration is accompanied with the photoluminescence peak energy shift from 0.73 to 0.67 eV. The effect by the annealing in the N2 atmosphere is found to be very small. These facts indicate that donor species involved in the MOVPE InN are passivated by oxygen. No structural changes such as a change in FWHM for X-ray rocking curve are found after the annealing.

Thin GaN Interlayer on a High Temperature AlN Buffer: Tao Wang; ‘University of Sheffield

We have investigated multiwavelength emitting InGaN/GaN quantum wells (QWs) formed on V-shaped GaN (1-101) microfacet. After a metalorganic chemical vapor deposition of 2μm thick GaN, SiO2 mask stripes were formed along GaN <11-20> direction by a conventional photolithography.
Subsequent regrowth of GaN generated the V-shaped (1-101) microfacets along <11-20> direction. Finally, five-period InGaN/GaN multiple QWs were fabricated on these microfacets. Interestingly, cathodoluminescence (CL) spectra measured on the microfacets showed a continuous change in the luminescence peak positions. The CL peaks were shifted to a longer wavelength from 420 nm to 440 nm as the probing points went up. We found in transmission electron microscopy that the growth rate of the QWs increased as it went up (not shown). Therefore, this nonuniform color distribution is considered to be due to the source depletion at the bottom of the microfacets.

**MOVPE Growth of GaN on Si(110) and Higher Index Planes:**

- **MOVPE High Quality GaN Films Grown on Si (111) Using AlN Multi-Layer Buffer:**
  - GaN grown on Si(111) is already a well established commercially available product and on Si(001) devices were recently demonstrated. On both surfaces GaN grows with c-axis orientation with much inferior quality on Si(001) than on Si(111) due to a poorer matching of atomic bonds at the interface. We have investigated the growth of GaN on surfaces with a two-fold symmetry, e.g., Si(110) or Si(115). On Si(110) the c-axis oriented AlN seed layer has only a mismatch of 0.7% for AlN <1-100> || Si <110> if every second plane is taken into account and 19% for the perpendicular direction, the latter similar as for the growth on Si(111). Compared to the growth on Si(111) the tilt and twist values for GaN/Si(110) are reduced by a factor of 1.5 and 2.5, respectively for a simple structure. Moreover, the Si(110) surface is interesting for wet chemical etching, and easier cleavage.

- **MOVPE Growth of GaN on LiNbO3 Substrate:**
  - For the first time, the growth of monocrystal GaN on 2-cut oriented LiNbO3 by metal organic vapor phase epitaxy (MOVPE). Novel growth conditions have been explored. Good surface morphology and crystalline quality of GaN on LiNbO3 has been obtained. In this presentation, the novel growth conditions as well as structural, electrical and optical characterization will be presented.

**MOVPE Films Growth Using AIN Multi-Buffer Layers:**

- **Kuang-Ling Lin**: High quality GaN films grown on Si (111) substrates using AIN multi-buffer layers have been studied by MOVPE processes. The GaN films with various buffer layers structures grown at different process conditions have been evaluated using XRD, OM, PL, SEM and AFM measurements. The experimental results show that the AIN film quality and film thickness are critical for growth of crack free GaN films on Si. The cracks formed in a single layer of HT AlN film on 6° Si (111) with thickness higher than 20 nm, but a 100 nm crack free AlN films with multi-layer of HT-AlN/HT-AIN can be obtained. Using the AIN multi-buffer layers, 0.5 μm crack-free GaN film can be grown on Si(111), GaN film (2μm thick) with GaN(004) Mosaic FWHM of 0.12° can also be achieved. The relationship between buffer layer structure, GaN film properties and process conditions are also discussed.

**Nonpolar m-Plane GaN and InGaN/GaN Multiple Quantum Well Light Emitting Diodes Grown Directly on γ-LiAlO2 by MOCVD:**

- **C. Specular**: The structure and surface properties of the epilayers were characterized by X-ray diffraction (XRD), Polarized Raman scattering and atomic force microscope (AFM). The films had a very smooth surface with a root mean square roughness as low as 2nm for a 10μm2 square by AFM scan area. The XRD spectra show that the material grown on LAO(100) have <1-100> m plane. The EL spectra of the M-plane InGaN/GaN multiple quantum well LED are shown. The current voltage characteristics of these LEDs showed rectifying behavior with a turn on voltage of 1-3V. Figure 1 shows the EL spectra and the current voltage characteristics (I-V) of the LED.

**Optimisation of AlInN/GaN HEMT Structures Grown by MOVPE:**

- **Lars Rahimzadeh Khosroshooy**: We report on the growth and characterisation of 190 nm thick Al0.83In0.17N layers and AlInN HEMT structures on GaN/sapphire. HRXRD rocking curve measurements exhibit FWHM values of 68 and 175 arcsec for the GaN (0002) and (10-15) reflex, respectively. The corresponding AlInN reflexes yielded 321 and 582 arcsec. In reciprocal space mappings (RSM) of GaN, a mosaic spread of 70 arcsec was measured, which is an indication of a comparably low threading dislocation density. Further, no spindal decomposition is detected for AlInN in both symmetrical and asymmetrical RSM. RBS and HRXRD measurements showed comparable in contents and matched well with simulations. Electrical characterisations of the HEMT at room temperature yielded a charge carrier density of $n_t = 1.88 \times 10^{10}$ cm$^{-2}$ and a mobility of $\mu = 1410$ cm$^2$/Vs. Further optimisation of the AlNn material quality by fine-tuning the deposition parameters is currently carried out.

**Photoluminescence Study of AlGaN/AlGaN Quantum Well Structures for Deep UV Emitters – Barrier Height and Well Width Dependence, and Growth Interruption Effect:**

- **M. Wienecke**: We investigate the growth of AlGaN/AlGaN multiple quantum well (QW) structures with different Al content. The effect of growth interruption in the AlGaN/AlGaN QWs, where only the III-group sourced were stopped, was also verified. We reconfirmed these issues to improve the emission efficiency. As results, higher-barrier and narrower-well QWs improved the PL intensities than the conventional ones. The effect of growth interruption in the AlGaN/AlGaN QWs, where only the III-group sourced were stopped, was also verified. Only several second interruptions made some crystalline damages at the interrupted surfaces. This may be due to the difference in desorption from the surface between Ga and Al atoms. We are developing AlGaN-based deep UV emitters grown by MOVCD. Barrier-height and well-width dependence, and growth interruption effect of AlGaN/AlGaN quantum well (QW) structures are investigated by photoluminescence (PL) measurements. In the previously reported deep UV emitting QW heterostructures, relatively low-height barriers (about 5% Al-content difference from the wells) and wide wells (4 ~ 6 nm) were adopted. We are developing deep UV emitters with different barrier heights and well widths, which are currently fabricated. The effect of growth interruption in the AlGaN/AlGaN QWs, where only the III-group sourced were stopped, was also verified. Only several second interruptions made some crystalline damages at the interrupted surfaces. This may be due to the difference in desorption from the surface between Ga and Al atoms. We are developing AlGaN-based deep UV emitters grown by MOVCD. Barrier-height and well-width dependence, and growth interruption effect of AlGaN/AlGaN quantum well (QW) structures are investigated by photoluminescence (PL) measurements. In the previously reported deep UV emitting QW heterostructures, relatively low-height barriers (about 5% Al-content difference from the wells) and wide wells (4 ~ 6 nm) were adopted. We are developing deep UV emitters with different barrier heights and well widths, which are currently fabricated.
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Strain Relaxation and Morphological Evolution of Annealed Low-Temperature-Deposited AlN Nucleation Layers: Rafael Dalmau1; Ramón Collazo1; Seiji Mita1; Anthony Rice2; Zlatko Sitar1; North Carolina State University

AlN nucleation (buffer) layers (NL), >7 nm thick, were grown on (0001) sapphire substrates at 500-650°C by MOVPE and subsequently annealed at high temperature (≥1000°C) under different process atmospheres (NH3, H2, N2). The NL were analyzed by high resolution x-ray diffraction (HRXRD), atomic force microscopy (AFM), and glancing angle x-ray reflectivity (XRR) to study the evolution of strain, crystallinity, morphology, and thickness as a function of annealing treatment. HRXRD indicated that NL grew under compressive strain and annealing changed the NL strain. Surface roughening of annealed NL was observed by AFM. The thermodynamic stability of AlN at annealing temperatures suggested that the driving force for roughening was strain, while differences in annealed NL thickness and morphology observed by XRR and AFM revealed the role of annealing atmosphere in NL evolution. The suitability of NL annealed under different conditions for growth of GaN and AlN epilayers will also be discussed.

Two-Dimensional Electron Gas Formation in AlGaN/AlGaN Heterostructures Grown by MOCVD: Mitsuaki Takeuchi1; Takuma Nanjo2; Muneyoshi Suita3; Yuki Abe4; Toshiyuki Oishi1; Yasunori Tokuda5; Yoshinobu Aoyagi6; 1RIKEN; 2Mitsubishi Electric Corporation; 3Tokyo Institute of Technology

Two-dimensional electron gas formation in AlGaN/AlGaN heterostructures grown by MOCVD is reported. As our best knowledge, this is the first report about these structures. Due to wider bandgaps of AlGaN layers than GaN, shift to higher Al-content structures will surely lead to higher power operation of electrical devices. To improve the AlGaN layer quality, we adopted thin GaN buffers which were developed for our new-concept vertical-type deep-shift to higher Al-content structures will surely lead to higher power operation of these structures. Due to wider bandgaps of AlGaN layers than GaN, electrical characterization confirms the ability of these thin barriers to form a 2DEG and efficiently block the current. The RTD structures show a reproducible negative differential resistance (NDR), which appears only when scanning from negative to positive bias. These results suggest that the NDR should be interpreted as a bi-stable behavior. It is possible to switch from one state to the other by applying an absolute voltage larger than about 4V. For bias higher than this threshold, time resolved measurements reveal a random transition between both states.

Near Ultraviolet Light Emitting Diode Composed of N-GaN/ZnO Coaxial Nanorod Heterostructures on a P-GaN Layer: Sung-In An1; Gyu-Chul Yi1; POSTECH

One-dimensional nanorod heterostructures which show compositional modulations along either axial or radial direction offer the opportunity to design numerous novel structures for optoelectronic device applications. Despite the successful demonstration of nanodevices based on the nanorod heterostructures, practical use of the nanodevices has remained out of reach since a necessary use of tedious e-beam lithography makes it difficult to manipulate nanodevices for nanofabrication. Here, we report on fabrications and characteristics of high efficiency nanorod LEDs using n-GaN/ZnO nanorod heterostructures on p-GaN substrates. The nanorod LEDs were turned on a forward bias voltage of 5 V, and exhibited strong emission from a large light emitting area. From EL spectra, dominant emission peaks were observed at 2.96 and 3.24 eV. The strong and large area light emission at near UV may result from the enhanced carrier injection from n-GaN nanorods to p-GaN substrates due to quantum confinement effect in the n-GaN nanorods.

Nonlithographic Nanopatterning of InGaN/GaN Multiple Quantum Wells Nanopillars by Focused Ion Beam Milling: Tzu-Hung Hsueh1; Shang-En Wu1; Chuan-Pu Liu2; Jinn-Kong Sheu3; Wei-Chih Lai1; Shou-Jung Chang4; 1National Cheng Kung University

Site-control InGaN/GaN multiple quantum wells (MQWs) nanopillars have been fabricated by nonlithographic nanopatterning technique of focused ion beam (FIB) milling. 30 keV Ga ions with a beam current of 300 pA have been applied to completely remove the III-V material around the pillars. Sharp-tip array and high-aspect-ratio InGaN/GaN MQW pillars are achieved by stigmating and defocusing the ion beam simultaneously. High-resolution scanning electron microscope and high-resolution transmission electron microscope images show that the pillars have diameters of around 100 nm to 150 nm and MQWs structures are embedded in the nanopillars. The FIB-patterned InGaN/GaN MQW nanopillars have an amorphous structure around the body of pillars. Emission spectra of InGaN/GaN MQW embedded in the pillars are observed around 2.98 eV by cathodoluminescence measurement in room temperature which showed a blue shift of about 35 meV compared with that of the as-grown wafer.
Photoelectrochemical Wet Etching of m-Plane GaN for Smooth, Low Damage Etching of Optical Devices. Adele Tamboli¹; Elaine Haberer¹; Matthew Schmidt¹; Kwang Choon Kim¹; James Speck¹; Steven DenBaars¹; Shuji Nakamura¹; Evelyn Hu¹; 'University of California, Santa Barbara

Wet etching provides many advantages for device processing, such as low damage etching and the formation of undercut structures. Photoelectrochemical (PEC) etching is a promising technique for wet etching of nitrides. We have previously reported on the formation of high quality undercut structures including c-plane microdisk lasers with record low thresholds. However, PEC etching of c-plane GaN is complicated by the built-in polarization, which alters the bandgaps of heterostructures and can compromise etch rates and selectivity. Additionally, it has been difficult to get high quality, smooth surfaces using PEC etching of c-plane GaN on sapphire because of the high defect density and defect-selective nature of PEC etching. However, we have observed both undercut and top-down etched surfaces with unprecedented smoothness using PEC etching of m-plane GaN on bulk substrates. We will discuss applications of PEC etching to devices including microdisks, photonic crystals, and microcavity LEDs.

Physical Properties of Nitride Nanorod Heterostructures: Li-Wei Tu¹; Y. T. Lin¹; Y. J. Tu¹; M. Chen¹; C. L. Hsiao¹; M. H. Tsai¹; H. W. S. Seo¹; Q. Y. Chen¹; W. K. Chu¹; 'National Sun Yat-Sen University; 'National Taiwan University; 'University of Arkansas; 'University of Houston

Under proper control of the growth conditions, III-V compound nitride semiconductors in nanorod structures can be obtained through the technique of molecular beam epitaxy (MBE). The MBE system uses N₂ plasma as the nitrogen source and solid metals for other group III elements. Substrates are mainly Si (111) wafers. Pure binary and ternary compound and various heterostructural nanorods are grown. All the nanorods line up vertically along the crystallographic c-axis of the hexagonal phase. Density of the nanorods can be varied from low 10⁷ to 10⁹ cm⁻³ with different geometrical shapes. Extensive characterizations are performed, such as field-emission scanning electron microscopy (FESEM), cathodoluminescence, (CL) photoluminescence (PL), x-ray diffraction (XRD), transmission electron microscopy (TEM), Raman spectroscopy, etc. Light-emitting diodes (LEDs) are fabricated out of these nanorods. Visible light emission is achieved using InGaN nanodisk as the active layer sandwiched between n- and p-type GaN nanorod. Electroluminescence (EL) spectra are measured.

Resistivity Study of Si-Doped GaN Nanowires Grown by Catalyst-Free MBE: Lorelle Mansfield¹; Paul Blanchard¹; Ari Sanders¹; Devin Rourke¹; Norman Sanford¹; Kris Bernsen¹; 'National Institute of Standards and Technology

Using two-terminal devices and a simple resistivity model, we estimated the bulk resistivity and carrier concentration of silicon-doped GaN nanowires grown by catalyst-free molecular beam epitaxy. Specific contact resistivity was calculated with an uncertainty of less than 20%. Contacts were fabricated to single nanowires with a Ti/Al metallization scheme. Using current-voltage curves to determine the resistance of several wires from each growth run and SEM to measure the dimensions, we calculated a specific contact resistance of 1.9×10⁻⁵ O•cm². We also estimated a bulk resistivity of approximately 0.003 Ω•cm and a free carrier concentration in the nanowires on the order of 2×10¹⁹ cm⁻³. Moderately doped nanowires had a specific contact resistivity of 1.9×10⁻⁴ Ω•cm². We also estimated a bulk resistivity of approximately 0.003 Ω•cm and a free carrier concentration in the nanowires on the order of 2×10¹⁹ cm⁻³. High-frequency measurements had a specific contact resistivity of 1.9×10⁻⁴ Ω•cm². We also estimated a bulk resistivity of approximately 0.003 Ω•cm and a free carrier concentration in the nanowires on the order of 2×10¹⁹ cm⁻³.

Ultraviolet Light-Emitting Diodes with Self-Assembled InGaN Quantum Dots: H. Kye Park¹; Min-Ki Kwon¹; Chu-Young Cho¹; Ja-Yeon Kim¹; Seong-Ju Park¹; 'Gwangju Institute of Science and Technology

A photoluminescence study showed that the self-assembled InGaN quantum dots (QDs) provide strongly localized recombination sites for carriers and that the piezoelectric field-induced quantum-confined Stark effect (QCSE) is small because the height of QDs is too small to separate the wave functions of electrons and holes. The InGaN QD light-emitting diode (LED) showed an emission peak at 400 nm and the peak was red-shifted with increasing injection current, indicating a small QCSE in InGaN QDs. The light output power of an InGaN QD LED increased linearly with increasing injection current due to the strongly localized recombination sites of the InGaN QDs.

Wide Bandgap Semiconductors as High-Electron Velocity Structures for Nanoelectronics: Mark Johnson¹; D.W. Barlage¹; 'North Carolina State University

Compound semiconductors have received recent attention as alternatives to silicon for aggressively nano-sized electronics, particularly for devices with gate lengths less than 22 nm. While much of the current research focuses on high-mobility narrow bandgap semiconductors, GaN or SiC have significant potential as alternative channel materials due to their high electron velocity. Under high source-to-drain field condition, we have identified a high peak velocity, low dielectric constant and high electron velocity saturation field as important physical parameters for alternative channel selection. We report on modeling and characterization studies aimed at identifying alternative channel materials for sub-22 nm nanoelectronics. This work considers Schottky source-drain injection into semiconductor channel, with corresponding high-K gates as device structures. Relevant device metrics such as CV/I, cut-off frequency and low threshold voltage as are used to assess nanoscaled silicon. This work points to the significant potential as well as critical challenges for SiC or GaN in nanoelectronics.

Quantum Dots: Characterization

Fabrication of GaN/AlN Bilayer Particles by a Vapor Phase Method: Kazuhiko Hara¹; Tatsuhiro Mori¹; Hironori Komoda¹; Yunya Ooig¹; Hitoko Kominami¹; Yoichiro Nakahishi¹; Shizuoka University

In contrast to the conventional powder phosphors consisting of particles with a uniform material composition, we propose GaN-based nanostructure-embedded particles, which consist of GaN quantum dots or quantum wells in the AlN matrix. We can expect the novel phosphors to have higher luminescence efficiencies owing to the carrier confinement effect. As the first step for the goal, we have demonstrated the formation of AlN core particles, and the subsequent deposition of GaN on the surface of the core particle by a vapor phase method. The AlN core particles with a diameter of about 200 nm were first formed by a reaction of vaporized Al and N₂ gas at 1200°C, followed by the growth of about 150-nm-thick GaN on the core surface by a reaction of GaCl and NH₃ at 1000°C. Thus fabricated GaN/AlN bilayer particles showed cathodoluminescence dominated by the band edge emission of GaN.

In-Situ Measurement of the Strain Relaxation of GaN Nanograins during X-Ray Irradiation: Hyoeum Cho¹; Sanghwa Lee¹; Yari Sohn¹; Taegeon Oh¹; Jai Weon Je¹; Chinkyo Kim¹; Kyunghee University

The absence of lattice-matched substrates for growth of GaN thin films was a major hindrance to fabricate high-performance GaN-based optoelectronic devices. On the other hand, it has been reported that lattice-mismatched layers can be grown without introducing misfit dislocations at the interfaces in nanorods and one of the issues in fabricating nanodevices is to carefully investigate their thermal stability. Due to the small volume of individual nanorods, the thermal stability of these nanostructures is of great importance in nanodevices. In this work, GaN nanograins were grown on c-plane sapphire substrates and their thermal stability was investigated by utilizing synchrotron x-ray scattering. The sample was constantly exposed to the synchrotron x-ray source and repeated θ-2θ scans were sensitive to the thermal stability of the nanograins under x-ray irradiation. Interestingly the peak position shifted to a higher θ-value implying that the GaN nanograins in compress strain experienced strain relaxation during x-ray irradiation.

Mobile and Immobile Photoluminescence Band from Single Hexagonal GaN Quantum Dots Formed in an AlN Matrix: Konstantin Zhuravlev¹; Vladimir Mansurov¹; Andrei Nikitin¹; Mats Larsson¹; Per Olof Holtz¹; 'Institute of Semiconductor Physics

Screening of built-in electric field in GaN/AlN hexagonal quantum dots (QDs) by non-equilibrium carriers have been studied by micro-photoluminescence (PL) spectroscopy. The QDs were grown by a particular
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MBE mode without a wetting layer. Typical dot density measured by transmission electron microscopy was $10^{11}$ cm$^{-2}$. The laser spot was 1.5 mm in diameter, the maximal excitation power was 6 mW. Sharp emission bands have been found on a low energy side of a broad PL band originating from QDs. Most of these PL bands do not shift with the excitation power varied at four orders of magnitude that evidences in negligible screening effect, while few tens of electro-hole pairs can be expected in single QD at the highest excitation power. A peculiar PL band blue-shifts with increasing excitation power. The blue shift is interpreted as being due to local electric fields induced by charged defects placed in vicinity of QD.

MOCVD Growth and Optical Properties of InGaN Quantum Dots on a Low Dislocation-Density GaN Surface Grown Using a High Temperature AlN Buffer: Tao Wang; Qi Wang; University of Sheffield

It is extremely difficult to achieve III-nitride quantum dot with a good uniformity. We believe that the major reason is due to a high dislocation density in III-nitride layer. Recently, we developed a so-called high temperature AlN buffer layer approach for GaN growth on sapphire by MOCVD. TEM indicated that the dislocation density is significantly reduced, compared to the conventional GaN layer. X-ray diffraction showed a less than 100 arcsec of FWHM of the symmetrical rocking curve of the GaN, which is massively narrower than that of the conventional GaN. Our InGaN QDs were grown on such high-quality GaN surface, and a significant improvement in dot uniformity has been achieved, which is much better than that grown on the conventional GaN surface. Photoluminescence (PL) measurements show a strong PL emission at 510 nm observed even on the QDs without any capping layer.

Rump Session I

Tuesday PM  Room: 314/315
September 18, 2007  Location: MGM Grand Hotel Conference Center

Program to be announced.

Rump Session II

Tuesday PM  Room: 312/317
September 18, 2007  Location: MGM Grand Hotel Conference Center

Program to be announced.
Session V: Solid State Lighting and LEDs

Wednesday AM
September 19, 2007
Room: 313/316
Location: MGM Grand Hotel Conference Center

9:00 AM Invited
V1, Recent Developments of High Efficiency White Light Emitting Diodes: Jukio Narukawa; Masahiko Sano; Takahiko Sakamoto; Takao Yamada; Takashi Mukai; Nichia Corporation

The multiple quantum well structure LED epitaxial layers were grown on the patterned sapphire substrate by MOOV. An indium-tin oxide (ITO) contact was employed as a p-type electrode. The LED chips were mounted on a lead frame (NICHIA RIKOH) and molded in an epoxy resin. At 20 mA under DC operation, the power output, forward voltage, peak wavelength, external quantum efficiency, wall-plug efficiency of the blue LED were 42.2 mW, 3.10 V, 443 nm, 75.4%, 68.1%, respectively. The luminous flux, forward voltage, luminous efficacy, wall-plug efficiency, color temperature and CIE chromaticity coordinates of the white LED were 9.86 lm, 3.10 V, 159 lm/W, 46.2%, 4840 K, (0.352, 0.375), respectively, at 20 mA. This value of luminous efficacy is about two times higher than that of fluorescent tubes. The GaN-based white light source will replace conventional lamps and will be suitable for tailor-made solid-state lighting.

9:30 AM
V2, Spectral and Time Resolved Scanning Near-Field Microscopy of Broad Area 405 nm InGaN Laser Diode Dynamics: Harald Braun; Tobias Meyer; Dominik Schulze; Ulrich Schwarz; Stefanie Brininger; Alfred Leitl; Uwe Strauss; University Regensburg; OSRAM Opto Semiconductors GmbH

Ridge widths of GaN lasers are typically in the order of few μm. In contrast to GaAs material systems, beam quality of GaN broad area lasers above 10μm is still a critical point. By time resolved scanning near-field microscopy on pulsed electrically pumped LEDs with different ridge widths we observe dynamic features caused by thermal and carrier induced changes of the refractive index like filamentation, lateral mode competition and beam steering, which strongly influence the far field of the LDs. Using a high spectral resolution spectrometer we can additionally resolve the individual longitudinal modes of the laser spectrum both time resolved on a 10 ns scale and correlated to the lateral position in the waveguide. Especially on samples with broad ridges we observe complex spectral and spatial dynamics of the laser mode like different filaments lasing dynamically on different longitudinal modes.

9:45 AM
V3, InGaN/GaN Multi-Facet Light Emitting Diodes toward Tailor-Made Solid-State Lighting without Phosphors: Mitsuura Funato; Takeshi Kondou; Keita Hayashi; Masaya Ueda; Yoichi Kawakami; Kyoto University; Nichia Corporation

InGaIn/GaN light emitting diodes (LEDs) were fabricated on GaN multi-facet structures, where (0001) and [11-22] microfacets are naturally formed by an MOVPE regrowth technique using mask stripes along the [1-100] direction. Electroluminescence was achieved by optimizing Mg-doping to GaN and device processes such as photolithography on multi-facet structures. The EL colors were confirmed to be different between (0001) and [11-22] facets due to the facet dependent InGaN composition and thickness. The additive color mixture produced intermediate colors. Because changing growth conditions and mask geometries can alter the shape of the microfacet structures, the emission colors are highly tunable. Conventional techniques to control the emission color are, for example, LEDs pumping phosphors and stacked QWs emitting different colors. The multi-facet LEDs can avoid Stokes loss observed in phosphors and have much higher emission color controllability, compared with stacked QWs. Therefore, we believe that our LEDs are suitable for tailor-made solid-state lighting.

10:00 AM
V4, Improved Performance of GaN-Based Deep Green Light Emitting Diodes through V-Defect Reduction: Theeradetch Detchprohm; Mingwei Zhu; Wei Zhao; Yong Xia; Yufeng Li; Jayantha Senawiratne; L. Liu; D. Hanser; Christian Wetzel; Rensselaer Polytechnic Institute; Kyuma Technologies, Inc.

We developed green light emitting diode (LED) dies covering the wavelength range of 525 to 570 nm (dominant). Active regions of GaInN/GaN quantum wells were grown in c-plane MOVPE GaN on sapphire and GaN substrate. Conventional epilayer growth is known to decorate threading dislocations in the active region with V-defects at densities of 10^8 to 10^9 cm^-2. These defects either emanate from the GaN buffer or originate in the quantum wells. This, in particular in green and deep green emitting dies, leads to rough growth morphology, drift of well and barrier widths, emission linewidth broadening, and large color shift with current density. Our alternate approach results in virtually V-defect-free layers and so avoids those effects to a large extend. In addition, electroluminescence output power nearly doubles while a slightly shorter emission wavelength can be compensated for. Findings are substantiated in large sets of scratch diodes and individual fabricated dies.

10:15 AM
V5, High Light Efficiency and Low Forward Voltage InGaN-Based Light Emitting Diode for Illumination: Seung Wan Chae; Chung Bae Jeon; Gun Yoo Ko; Seok Min Hwang; Je Won Kim; Yong Chun Kim; Yoon Seok Han; Jong Rak Son; Samsung Electro-Mechanics

In this study, in order to achieve a low-resistance and highly transparent ohmic contacts to p-GaN for high power LEDs, we focused on development of ohmic contact layer between the p-GaN and the ITO. For this purpose, we fabricated the light emitting diode by using CIO/ITO contact on p-GaN and the patterned sapphire substrate. Then, we compared the contact resistance as well as the transmittance of the ITO electrodes contact, compared to Ni/Au electrode. Among the various ohmic contact layers, the CIO/ITO contacts showed a high transmittance over 92% at 460nm and a low contact resistance lower than 10^-3Ωcm. In addition, the fabricated InGaN LEDS showed a low forward voltage (Vf) of 3.28V and a luminescence of 256mW at 350mA operation with the CIO/ITO transparent contacts better than Vf of 3.25V and a luminescence of 170mW with Ni/Au contact, respectively.

10:30 AM
V6, New Design of GaN Vertical Light Emitting Diodes on Metal Substrate for Solid State Lighting Application: Chen-Fu Chu; Chao-Chen Cheng; Wen-Huan Liu; Jiunn-Yi Chu; Feng-Hsu Fan; Hao-Chun Cheng; Jui-Kang Yen; Trung Doan; Chuong Tran; Semi-Photonics; SEMILedS

The new design of the GaN based Vertical Light Emitting Diodes on Metal Substrate (VLEDMS) for high power solid state lighting application has been investigated. The VLEDMS exhibits low operation voltage of 3.1 V at 350 mA and can sustain much higher current, up to 3A without any performance deterioration. The low operation junction temperature of VLEDMS demonstrates excellent heat dissipation capabilities. Chip scaling can be done successfully without efficiency loss up to 80 mil chip size, shows the unique property of VLEDMS. A light output efficiency of over 100 lms/watt has been achieved in 40 mil single VLEDMS chip package. Our chips showed only a small decline in light output power over time; this change can be kept below 15% under 350mA and 700mA driving current and room temperature after 3000 hours burn-in test. Coupled with mass production ability, VLEDMS is the ideal choice for solid state lighting application.

10:45 AM
V7, Enhancement in Light-Extraction of GaN Light-Emitting Diodes by Using Indium-Tin-Oxide Graded-Refractive-Index Antireflective Contacts: Jong Kyu Kim; Sameer Chhajed; Martin Schubert; Jaehee Cho; Hyunsoo Kim; Cheolsoo Sone; E. Fred Schubert; Rensselaer Polytechnic Institute; Samsung Electro-Mechanics Company Ltd

The refractive of a thin-film material, which is chosen for its desirable conductive and transparent properties, can be precisely tailored by using oblique-angle deposition technique. As an example, we demonstrate six-layer graded-refractive-index antireflection coating made entirely of indium-tin-oxide (ITO) which is chosen for its high conductivity, high optical
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transmittance, and low contact resistance with p-type GaN. Each ITO layer has an individually tailored thickness and refractive index ranging from 2.19 to 1.17 to follow the modified-quintic-index profile for an optimum anti-reflection performance. Blue GaN N light-emitting diodes with the ITO graded-refractive-index antireflective contacts achieve a light-extraction efficiency enhanced by 24.2% compared to LEDs with conventional ITO contacts due to a strongly reduced Fresnel reflection.

11:00 AM Break

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Session W:
Nonpolar and Semipolar Materials and Devices II

Wednesday AM  
September 19, 2007  
Location: MGM Grand Hotel Conference Center

9:00 AM  
W1, Homoeptaxial Growth of Nearly Stacking-Fault-Free m-Plane (In,Ga)N Films by Metalorganic Vapor Phase Using Low Defect Density Free-Standing Substrates: Shigefusa Chichibu1; Masashi Kubota2; Hiroshi Yamaguchi3; Lu Zhao4; Kenyoshi Okamoto5; Hiroyuki Ohta6; Tohoku University; University of Tsukuba; Rohm Company Ltd.

Nearly stacking fault-free m-plane GaN and InGaN films were grown by MOVPE on the free-standing (FS) m-plane GaN substrates, which were cut from c-plane FS GaN substrates prepared by HVPE (Mitsubishi Chemical). The threading dislocation density of the epilayers was lower than 5x10^6 cm^-2 and the surface AFM image exhibited atomically-flat morphology with well-aligned monolayer steps. The FWHM values of the x-ray rocking curves for both GaN and InGaN were close to the values of the substrate (31 arcsec for the (0001) azimuth). Low temperature PL spectra of GaN epilayers exhibited well-resolved band and free exciton lines, which obeyed the polarization selection rules. PL lifetimes of GaN epilayers at room temperature, which can be a representative of nonradiative lifetime, increased with increasing V/III ratio and the values for m-plane GaN were much lower than those of c-plane GaN grown on (0001) Al2O3 substrates. The InGaN epilayers exhibited single peak emissions.

9:15 AM  
W2, m-Plane GaN/InGaN/AlInN on LiAlO2 Grown by MOVPE: Y. Diki2; H. Behmenburg3; Ch. Giesen4; M. Chou5; M. Heuk6; 1AIXTRON AG; 2National Sun Yat-Sen University

The growth of non-polar material leads to a more efficient recombination across the quantum well of GaN-based light emitting diode (LED) structures. Lithium aluminate (LiAlO2) offers the possibility to grow non-polar (m-plane) GaN. The scope of this work is the growth and the investigation of m-plane GaN-based layers on LiAlO2. All growth experiments have been performed in an MOVPE setup. The growth of non-polar GaN was confirmed by x-ray rocking curve measurements. The surface morphology of the templates is dominated by the presence of basal plane stacking faults with a density of around 3x10^6 cm^-2. Basal stacking faults are either terminated by partial dislocations or connected by prismatic stacking faults. Perfect a-type dislocations are also observed. ELO films with stripes parallel to {1-100} facet allow us to reduce the density of basal stacking faults in the overgrown regions down to 5x10^5 cm^-2. In these overgrown materials, the density of perfect dislocations is 10^6 cm^-2 while neither partial dislocation nor prismatic stacking faults are observed.

9:30 AM  
W3, p-Type Conduction in Stacking-Fault-Free m-Plane GaN: Mel McLaurin1; Feng Wu2; James Speck1; 1University of California, Santa Barbara

We report on transport measurements of p-type m-plane GaN grown on low defect density, free-standing m-plane (10-10) GaN substrates. The measurements showed no significant anisotropy in in-plane mobility—between the [11-20] and [0001] directions—for hole concentrations between 2.4x10^17 and 8.7x10^17 cm^-3. Hole mobilities where in good agreement with in-plane measurements of c-plane oriented films grown in previous studies. This is significant considering the expected anisotropy in effective hole masses for the valence bands of GaN. Since faulted m-plane films showed significant anisotropy in electron and hole mobilities, basal plane stacking faults, which have an anisotropic distribution, are discussed as a possible source of anisotropic scattering in non-polar and semi-polar films. The displaced material of the basal plane stacking faults is considered to be similar to zincblende GaN, resulting in discontinuities in the conduction and valence band edges at the zincblende/wurtzite polytype interfaces and the possibility of non-uniform carrier densities.

9:45 AM  
W4, Transmission Electron Microscopy Study of Semipolar GaN Templates and Epitaxial-Lateral-Overgrown Films Deposited on m-Plane Sapphire by Metalorganic Vapor Phase Epitaxy: Philippe Venneque1; Zahia Bourgrioua1; Tobias Guehne2; 1National Center of Scientific Research/Research Center on the Hétéro-Epitaxy and Its Applications; 2National Center of Scientific Research/Electronics, Microelectronics and Nanotechnology Institute

The microstructure of GaN templates and epitaxial lateral overgrown (ELO) films deposited on M-plane sapphire is investigated using different transmission electron microscopy techniques. The epitaxial relationship is [11-20]_GaN parallel to [1-100]_sapphire in-plane with a growth plane close to (11-22)_sapphire. A mechanism to explain this relationship is proposed. The microstructure of the templates is dominated by the presence of basal stacking faults with a density of around 3x10^6 cm^-2. Basal stacking faults are either terminated by partial dislocations or connected by prismatic stacking faults. Perfect a-type dislocations are also observed. ELO films with stripes parallel to [1-100]_sapphire allows us to reduce the density of basal stacking faults in the overgrown regions down to 5x10^5 cm^-2. In these overgrown materials, the density of perfect dislocations is 10^6 cm^-2 while neither partial dislocation nor prismatic stacking faults are observed.

10:00 AM  
W5, Microstructure of Non-Polar (11-20) and Semi-Polar (11-26) GaN Films Grown on c-Plane Sapphire by MBE: Lin Zhou1; David Smith2; R. Chandrasekaran3; T. Mousta4; 3Arizona State University, School of Materials and Department of Physics; 4Boston University, Department of Electrical and Computer Engineering

GaN films and GaN/AlGaN multiple quantum wells with (11-20) and (11-26) planes parallel to the R-plane of sapphire were grown by molecular beam epitaxy under different growth conditions. Transmission electron microscopy (TEM) analysis showed that both sets of films were single crystalline. High density of basal plane stacking faults (BSFs) was observed in the non-polar (11-20) GaN (n-GaN) films. Stacking faults (SFs) lying on (11-20), (10-10) prismatic planes and (10-102) pyramidal planes were also observed. The SFs on (11-20) and (10-102) planes generally formed closed domains. For semi-polar (11-26) GaN (s-GaN) films, threading dislocations were observed to form small angle grain boundaries. Most BSFs in the s-GaN film were propagated from the AlN buffer. SFs on (10-10) planes were also observed and formed by folding of the BSFs. SFs propagating to the top surface created some triangular and hexagonal shaped pits on the GaN surface.

10:15 AM  
W6, Fabrication and Properties of Semi-Polar (1-101) and (11-22) InGaN/GaN MQW Light Emitting Diodes on Patterned Si Substrates: Toshiki Hikosaka1; Tomoyuki Tanikawa1; Yoshio Honda1; Masahito Yamaguchi1; Nobuhiko Sawaki1; 2Nagoya University

InGaN/GaN MQW light emitting diodes (LEDs) were fabricated on semi-polar (1-101) and (11-22) GaN templates which had been grown on patterned (001) and (113)Si substrates, respectively, for the first time. The GaN templates were of 300 × 300 μm^2 “as-grown” square discs, formed by coalescence of appropriate GaN stripe structures made by selective MOVPE method. The MQW active layer was embedded between Si-doped n-type GaN bottom layer and Mg-doped p-type GaN top layer. The n-type electrode was facilitated by depositing AuSb on the back surface of the Si substrate. The turn-on voltage of the diodes was on the order of 3 - 4 V, and the emission intensity was linearly increased as a function of the drive current. The peak wavelengths at 20 mA were 470 nm and 453 nm, respectively, which were slightly blue-shifted at high drive currents.

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9:45 AM
X4, Effect of Hydrogen and Silicon Co-Doping in Ferromagnetic GaGdN Grown by MBE. Martin Roever; Amilcar Bedoya-Pinto; Dong-Du Mai; Joerg Malindretos; Angela Rizzi; Georg-August-Universitaet Goettingen

With the aim of understanding the observed room-temperature giant magnetic moment of highly diluted GaGdN reported in literature GaGdN, GaGdN:Si and GaGdN:H have been grown by molecular beam epitaxy (MBE) and the Gd concentration is between 10¹⁰ and 10¹¹ cm⁻³. All samples are ferromagnetic at 300 K as measured by SQUID and the very high saturation magnetic moment in this type of samples is confirmed by our experiments. With co-doping of hydrogen or silicon we were able to decrease or increase respectively the strength of the magnetic moments in the layers. All our findings indicate that ferromagnetism is stabilized by electrons. Electrical measurements on GaGdN layers grown on high resistive 6H-SiC(0001) show a typical temperature dependence of hopping conductivity. The overall resistance for a layer thickness of 500 nm is 2.3 to 290 MΩ in the temperature range from 60 to 10 K.

10:00 AM
X5, MBE Growth of Gadolinium Nitride and Its Integration with GaN: Michael Scarpulla; Chad Gallina; Arthur Gossard; James Speck; Materials Department, University of California, Santa Barbara

The integration of rock-salt rare earth pnictides with III-V semiconductors holds promise for enabling and enhancing devices. We have investigated the growth of gadolinium nitride and its integration with GaN using two types of molecular beam epitaxial (MBE) growth. We use nitrogen plasma assisted MBE (PAMBE) to grow GdN on (0001) Ga-face GaN and ammonia MBE (NH3-MBE) to deposit nanolayers embedded in GaN. Results from X-ray diffraction (XRD) on the GdN films demonstrate that GdN grows in the (111) || GaN(0001) orientation expected from symmetry considerations. Reflection high energy electron diffraction demonstrations that GdN nucleates and grows via a 3D mode in NH3-MBE growth. We will discuss the structural and optical properties of both films and superlattices formed by successive layers of GaN and GdN nanolayers. Finally, we will present results from efforts to enhance tunneling efficiency in GaN tunnel junctions by embedding GdN nanolayers in the junction.

10:15 AM
X6, Late News

10:30 AM
X7, Late News

10:45 AM
X8, Late News

11:00 AM Break

Session Y:
Optical and Structural Characterization and Related Topics

11:30 AM
Y1, Cumulative Growth and Microstructure Studies of Nonpolar m-Plane SLEO GaN: Kwang-Chooong Kim; Mathew Schmidt; Asaka Hirai; Makoto Saito; Feng Wu; Melvin McLaurin; Erin Young; Shuji Nakamura; Steven DenBaars; James Speck; University of California, Santa Barbara

Despite the clear advantages for optoelectronic devices, nonpolar m-plane GaN heteroepitaxy typically suffers from high densities of extended defects including threading dislocations (TDs) and stacking faults (SFs). Here, the
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growth characteristics and the microstructure of sidewall LEO of m-plane GaN grown by MOCVD and HVPE have been investigated. The application of SLEO to m-plane GaN heteroepitaxy yielded significant reduction on rocking curve FWHMs of on-axis (1100) reflection from 0.199° (φ=0°) and 2.589° (φ=90°) for template to 0.137° and 0.408° for SLEO, respectively, indicating the reduction of both TDs and SFs. The XTEM images confirmed that TDs typically form only around the shoulders between masks and openings, and SFs typically form not only at the shoulders but also over N-wing regions over SiO2 masks, moreover, SF annihilation by forming loops during the lateral growth was observed. Surprisingly, changing the mask geometry yielded the fast coalescence and SF-absent N-wings grown over SiC.

11:45 AM

Y2, Design, Growth, Fabrication, and Characterization of GaN and InGaN Solar Cells: Xiaodong Chen; Kristopher Matthews; Dong Hao; William Schaff; Lester Eastman; ‘Cornell University

The InGaN alloy system offers a unique opportunity to develop high efficiency multi-junction solar cells. In this study, single junction solar cells made of GaN and InGaN are successfully developed. The materials are grown on sapphire substrates by MBE, consisting of a Si-doped n-type layer, an intrinsic layer and an Mg-doped p-type layer on top. The IV curves indicate that the cell made of GaN has low series resistance (0.12 ohm-cm2) and parasitic leakage is insignificant. Contact resistances of p and n contacts are 74 O-mm and 0.2 O-mm respectively. Upon illumination by a 325 nm laser, the cell shows a clear photo-response with a fill factor of 61% and Voc=2.5V. In InGaN cell with 20% In content, the photo-response is also observed when illuminated by outdoor sunlight (~600suns). But it has been dominated by a big leakage current, which might be caused by the defects.

12:00 PM

Y3, Nitride Photocatalyst to Generate Hydrogen Gas from Water: Yashhiro Iwaki; Kazuki Yamaguchi; Kazuhide Kusakabe; Katsushi Fujii; Kazuhiro Ohkawa; ‘Tokyo University of Science; ‘Tohoku University

We report on the great potential of nitride photocatalyst in view of external quantum efficiency (EQE), and on properties of n-n+ structure nitride photocatalyst we proposed. EQE of a photocatalysis cell was measured by using monochromatic light. The EQE of the GaN cell was greater than 40% at >360nm. Using InGaN, the EQE value achieved 7.2% at 400nm in visible region. These EQE values are quite large compared to the conventional oxide photocatalysts. The depletion layer separates electrons and holes generated by photons. Holes move to the surface, and oxidize the electrolyte. On the other hand, electrons go to a counterelectrode for reduction through the layer. The layer should be conductive. Thus we propose a structure with an n-type layer for light absorption on a conductive n+-type layer. The n-n+ structure nitride photocatalyst improved H2 generation compared to a single n-GaN layer by 1.4 times.

12:15 PM

Y4, Very Low Dislocation Density GaN Films Obtained Using Transition Metal Nitride Interlayers: Michelle Morani; Yucheng Zhang; Menno Kappers; Zoe Barber; Colin Humphreys; ‘University of Cambridge

We present a simple method to reduce threading dislocation densities (TDDs) in (0001)-oriented GaN from 5 x 10^5 cm^-2 to as low as 5 x 10^4 cm^-2 in a single step, without lithography. Thin (5-25 nm) amorphous layers of Sc, Hf, Nb, Zr and Ti were deposited on GaN-on-sapphire templates and converted to nitrides by annealing in NH3. ScN layers show few cracks or pinholes after annealing, whereas other layers showed high densities of holes. GaN initially forms dislocation-free islands when grown on ScN layers. TDDs reach 1 x 10^4 cm^-2 for coalesced GaN grown on holey interlayers, but only 3 x 10^3 cm^-2 for coalesced GaN on ScN interlayers. Partially-coalesced GaN on ScN interlayers has dislocation-free regions of > 100 μm^2 and a TDD of ~5 x 10^4 cm^-2. TEM studies show that the interlayers block dislocation propagation, with some dislocations generated upon coalescence of GaN islands.

12:30 PM

Y5, Orders of Magnitude Reduction in Dislocation Density in GaN Grown on Si (111) by Nano Lateral Epitaxial Overgrowth: Soo-Jin Chau; Ke Yan Zhang; Ya Dong Wang; ‘Institute of Materials Research and Engineering; ‘Singapore-MIT Alliance

GaN grown on Si(111) by MOCVD has dislocation density on the order of 109 to 1010 cm^-2. In nanoscale lateral epitaxial overgrowth (NLEO), where the GaN is overgrown on SiO2 with nanopores etched into it, forming a selective area epitaxial mask on GaN/Si, the dislocation density in the resulting GaN is found to have dislocation density reduced by about 2 orders of magnitudes. The nanopores were etched on the SiO2 with anodic alumina template forming the etch mask. The mechanism of threading dislocation density reduction is due to dislocation bending and annihilation. The narrower band-edge emission in photoluminescence spectrum shows a better optical quality in the NLEO GaN film. High quality GaN nanorod arrays have also been grown through the nanopores with very low dislocation density.

12:45 PM

Y6, Effects of Compositionally Graded Al,Ga1-xN Buffer Layers on the Evolution of Threading Dislocations in GaN Films Grown on SiC and Si Substrates: Xiaojun Weng; Jeremy Acord; Abhishek Jain; Elizabeth Dickey; Joan Redwing; ‘Pennsylvania State University

The effects of Al,Ga1-xN buffer layers on the evolution of threading dislocations (TDs) in GaN films grown on SiC substrates by metalorganic chemical vapor deposition were studied and compared with the films grown on (111)Si substrates. Similar to the GaN/Al,Ga1-xN/Si heterostructures, significant TD bending and annihilation was observed in the Al,Ga1-xN buffer layers on SiC substrates, which subsequently led to reduced TD densities in the overgrown GaN films compared to those grown on SiC using thin AlN buffer layers. While the TDs in GaN films on (111)Si substrates are predominantly edge dislocations, the TD types in films on SiC substrates are affected by both the SiC surface morphology and the composition gradient of the Al,Ga1-xN buffer layers. Chemically-mechanically polished flat SiC surfaces lead to an increase in screw TD density, and a steeper gradient of Al,Ga1-xN promotes the formation of edge TDs. The mechanisms of TD selection will be discussed.

1:00 PM

Y7, Origin of Additional Threading Dislocations in AlGaN Grown on GaN Using an AIN Interlayer: Ranjan Dutta; ‘Arizona State University

Thick AlGaN layers with high Al contents grown epitaxially on GaN crack due to tensile strain arising from the lattice parameter mismatch. AIN interlayers can be used to prevent this cracking, but there is a concomitant increase in the edge-type threading dislocation density in the AlGaN film. In this contribution, the origin of the additional threading dislocations (TDs) is investigated. The interlayer itself micro-cracks to relieve strain, and overgrowth of AlGaN on such a relaxed/ cracked AIN layer gives rise to the formation of additional edge-type threading dislocations along the crack lines. This appears to be due to terminated misfit dislocation lines at the crack facets that are replicated during subsequent growth, resulting in additional edge TDs in the upper AlGaN layer. The contribution of cracks in generating additional edge TDs can also depend on whether the crack lines are filled or a void is created during AlGaN growth.

1:15 PM

Y8, Late News
We have grown non-polar (11-20), semi-polar (11-22), and polar (0001) GaN templates on r-plane, m-plane, and c-plane sapphire substrates, respectively, using metal-organic vapor-phase epitaxy. The (11-20) templates were grown using three SiN$_x$ interlayers to improve the films' structural characteristics. Ten period Al$_{0.8}$Ga$_{0.2}$N/GaN multiple quantum wells were then grown on each film orientation with 2nm, 3nm, 4nm, 5nm, and 6nm well thicknesses, and 10nm barriers. The structures were then analyzed to determine the thicknesses of the GaN wells and AlGaN barriers, and the Al$_{0.8}$Ga$_{0.2}$N composition using high-resolution X-ray diffraction, X-ray reflectivity, and transmission electron microscopy. The variation of 300K photoluminescence peak emission energy with quantum well width is consistent with a reduction or elimination in the quantum-confined Stark effect in wells with semi-polar (11-22) and non-polar (11-20) orientations, respectively. The results of detailed structural characterization, temperature-dependent photoluminescence, and theoretical modeling will be presented on all the structures.

### Session AA: Optoelectronic Devices

#### Z4, A Comparative Study of Non-Polar (11-20), Semi-Polar (11-22), and Polar (0001) AlGaN/GaN Multiple Quantum Wells: Jonathan Holland$^1$; Nicholas Hylton$^1$; Carol Johnston$^1$; Menno Kappers$^1$; Clifford McAleese$^1$; Phil Dawson$^1$; Colin Humphreys$^1$; University of Cambridge; $^2$University of Manchester

We have grown non-polar (11-20), semi-polar (11-22), and polar (0001) GaN templates on r-plane, m-plane, and c-plane sapphire substrates, respectively, using metal-organic vapor-phase epitaxy. The (11-20) templates were grown using three SiN$_x$ interlayers to improve the films’ structural characteristics. Ten period Al$_{0.8}$Ga$_{0.2}$N/GaN multiple quantum wells were then grown on each film orientation with 2nm, 3nm, 4nm, 5nm, and 6nm well thicknesses, and 10nm barriers. The structures were then analyzed to determine the thicknesses of the GaN wells and AlGaN barriers, and the Al$_{0.8}$Ga$_{0.2}$N composition using high-resolution X-ray diffraction, X-ray reflectivity, and transmission electron microscopy. The variation of 300K photoluminescence peak emission energy with quantum well width is consistent with a reduction or elimination in the quantum-confined Stark effect in wells with semi-polar (11-22) and non-polar (11-20) orientations, respectively. The results of detailed structural characterization, temperature-dependent photoluminescence, and theoretical modeling will be presented on all the structures.

#### Session Z:

### Non-polar and Semipolar Materials and Devices III

#### 11:30 AM Invited

**Z1, Local Spectroscopic Investigations on Semipolar InGaN-Based Nanostructures and Their Application to LEDs**: Yuichi Kawakami$^1$; A. Kaneta$^1$; K. Nishizaki$^1$; Masaya Ueda$^1$; Kazanobu Kojima$^1$; M. Funato$^1$; Y. Nakamura$^1$; T. Muka$^1$; Kyoto University; $^2$Nitrile Semiconductor Research Laboratory, Nichia Corporation

Nonmorphic optical characterization using scanning near-field optical microscopy (SNOM) was performed on a (11-22) microfacet quantum well (QW) fabricated by the re-growth technique. Unlike the phenomena observed in (0001) QWs, there is not a difference between the photoluminescence (PL) spectra acquired under the illumination-collection and illumination modes, which indicates that the carrier diffusion length in the (11-22) QW is less than the probing fiber aperture of 160 nm due to a much faster radiative recombination processes as a result of a well-reduction of internal electric field. The correlation between internal quantum efficiency (IQE) and emission wavelength is elucidated by comparing the PL intensity and wavelength mappings. The highest IQE is approximately 50% at 520 nm, and emission wavelength is elucidated by comparing the PL intensity and wavelength mappings.

**Z2, High Performance Violet-Blue and Blue LEDs on Freestanding Nonpolar (10-1-1) Bulk GaN Substrate**: Hong Zhong$^1$; Anurag Tyagi$^1$; Natalie Fellows$^1$; Feng Wu$^1$; Roy Chung$^1$; Makoto Saito$^1$; Kenji Fujito$^1$; James Speck$^1$; Steven DenBaars$^1$; Shuji Nakamura$^1$; University of California, Santa Barbara; $^2$Mitsubishi Chemical Corporation

Violet-blue and Blue InGaN/GaN multiple-quantum-well (MQW) light emitting diodes (LEDs) with peak emission wavelengths of 411 nm and 444 nm were grown on low extended defect density semipolar bulk GaN substrates by conventional metal organic chemical vapor deposition (MOCVD). Under dc operations, the electroluminescence (EL) peak emission wavelength of the violet-blue LED at 1 mA and 100 mA drive currents were 411 nm and 413 nm, respectively. Under pulsed operations (10% duty cycle), the EL peak emission wavelength of the blue LED ranged from 443.9 nm at 10 mA to 443.4 nm at 100 mA. At a forward current of 20 mA, we measured an output power of 20.58 mW and an external quantum efficiency (EQE) of 33.91% for the violet-blue LED under dc operations and an output power of 16.21 mW and an EQE of 29% for the blue LED under pulsed operations (10% duty cycle).

**Z3, High Quality Nonpolar and Semipolar GaN Films Grown on Lattice Matched ZnO Substrates at Room Temperature**: Atsushi Kobayashi$^1$; Kohei Ueno$^1$; Jitsuo Ohta$^1$; Hiroshi Fujiko$^1$; Hidetaka Amanai$^2$; Satoru Nagao$^1$; Hideyoshi Horie$^1$; University of Tokyo; $^2$Mitsubishi Chemical Group Science and Technology Research Center, Inc.

We have grown nonpolar and semipolar GaN films on nearly lattice matched ZnO substrates at room temperature (RT) by the use of pulsed laser deposition. ZnO crystals with various nonpolar and semipolar surfaces were used as substrates in this study. Structural and optical properties of GaN films were investigated with RHEED, AFM, HRXRD, RSM, and PL. All the GaN layers have exhibited sharp streaky RHEED patterns and small FWHM values for X-ray rocking curves, indicating that high-quality GaN films with various orientations grow epitaxially even at RT. We also found that RT growth of nonpolar and semipolar GaN on these substrates proceeds in the layer-by-layer mode. TEM observations have revealed that the heterointerfaces between RT-GaN and ZnO is quite abrupt, which is inherently important to take advantages of lattice matched ZnO substrates.

#### 12:00 PM

**Z4, A Comparative Study of Non-Polar (11-20), Semi-Polar (11-22), and Polar (0001) AlGaN/GaN Multiple Quantum Wells**: Jonathan Holland$^1$; Nicholas Hylton$^1$; Carol Johnston$^1$; Menno Kappers$^1$; Clifford McAleese$^1$; Phil Dawson$^1$; Colin Humphreys$^1$; University of Cambridge; $^2$University of Manchester

Carrier dynamics of InGaN quantum wells (QWs) grown on polar and semipolar GaN planes is correlated with direct measurements of the electrostatic potential using electron holography. The QWs were nominally 3 nm wide and the indium compositions were varied over a wide range in order to achieve c-plane emission from violet to yellow wavelengths. The recombinaction lifetime increases from 2 ns for the violet QW to 145 ns for the yellow QW. This trend in lifetime is correlated with a monotonic increase in the internal polarization fields from 0.4 MV/cm across the violet QW to 1.6 MV/cm across the yellow QW. Semipolar QWs, grown on [11-22] GaN planes, exhibit considerably smaller lifetimes (0.4-0.7 ns), which are found to be a relatively independent of well width and indium composition. Direct measurements of the electrostatic potential across these quantum wells confirm that the internal fields in this geometry are negligible.

#### 12:15 PM

**Z5, InGaN Quantum Wells on Polar vs. Semipolar GaN Orientations: Internal Fields and Their Effect on Luminescence**: Sridhar Srinivasan$^1$; Z. Wu$^1$; M. Stevens$^1$; F. Ponce$^1$; H. Omiya$^1$; T. Muka$^1$; Arizona State University; $^2$Nichia Corporation

Carrier dynamics of InGaN quantum wells (QWs) grown on polar and semipolar GaN planes is correlated with direct measurements of the electrostatic potential using electron holography. The QWs were nominally 3 nm wide and the indium compositions were varied over a wide range in order to achieve c-plane emission from violet to yellow wavelengths. The recombinaction lifetime increases from 2 ns for the violet QW to 145 ns for the yellow QW. This trend in lifetime is correlated with a monotonic increase in the internal polarization fields from 0.4 MV/cm across the violet QW to 1.6 MV/cm across the yellow QW. Semipolar QWs, grown on [11-22] GaN planes, exhibit considerably smaller lifetimes (0.4-0.7 ns), which are found to be a relatively independent of well width and indium composition. Direct measurements of the electrostatic potential across these quantum wells confirm that the internal fields in this geometry are negligible.
Technical Program

allows to determine the PhC dispersion curves and the extraction efficiency for the various waveguided modes. We finally discuss the optimization of PhC extractors for efficiency and brightness as it is strongly needed to make them competitive with other light extracting schemes, implying various options and technical challenges.

12:00 PM
AA2, Investigation of the Strong Exciton Photon Coupling in Hybrid AlInN/AlGaN Microcavities with GaN/AlGaN Multiple Quantum Wells: Gabriel Christmann; Raphaël Butte; Eric Feltin; Jean-François Carlin; Nicolas Grandjean; École Polytechnique Fédérale de Lausanne (EPFL)

We report on the observation of strong exciton-photon coupling at room temperature (RT) in hybrid AlInN/AlGaN microcavities containing multiple quantum wells (MQWs) grown by metalorganic vapor phase epitaxy on c-plane sapphire substrates. The structures consist of a strain relieving template, a 40 pair Al_{0.8}In_{0.2}N/Al_{0.2}Ga_{0.8}N distributed Bragg reflector (DBR) followed by a 3A cavity (λ = 343 nm) containing several narrow GaN/AlGaN QWs. The structures were completed by depositing a 13 pair SiO/SiN DBR. The interest in using GaN/AlGaN MQWs resides in their increased exciton binding energy and oscillator strength over bulk GaN layers. This ensures stronger light-matter coupling conditions as revealed by RT angle-resolved photoluminescence and reflectivity measurements revealing a vacuum Rabi splitting in excess of 50 meV, the highest value reported so far for a QW based microcavity. The interplay between polariton branches and Bragg modes is also seen to be significant at large angles in such system.

12:15 PM
AA3, Resonant Modes in GaN-Based Small-Volume Pillar Microcavities: Henning Lohmeyer; Kathrin Sebal; Jürgen Gutowski; Stephan Fiege; Timo Aschenbrenner; Heiko Dartsch; Carsten Kruse; Detlef Hommel; Jan Wiersig; Frank Jahnke; University of Bremen

The fabrication and the optical properties of GaN-based pillar microcavities with small mode volumes suitable for low-threshold lasers and control of spontaneous emission are discussed. Monolithic vertical cavities grown by molecular-beam epitaxy, and hybrid cavities employing one nitride-based Bragg reflector grown by metal-organic vapor-phase epitaxy are compared. Pillar structures with diameters between 800 nm and 3 μm have been fabricated by focused-ion-beam etching, yielding structures with smooth sidewalls and high aspect ratios. The discrete mode spectrum of the pillars has been studied by micro-photoluminescence measurements. The measured data for different pillar diameters show good agreement with calculations of the transmission spectra of the three-dimensional pillars based on a vectorial transfer-matrix method. The optical properties of structures with InGaN/GaN multiple quantum wells embedded are discussed as prototypes for vertical-cavity lasers. Additionally, emission properties of InGaN/GaN quantum-dot pillar microcavities are presented. H. Lohmeyer et al., Eur.Phys.J.B 48,291 (2005).

12:30 PM
AA4, Directional Emission III-Nitride Photonic Crystal LEDS: Jonathan Wiers; Aurelien David; Philips Lumileds Lighting

Employing photonic crystals in light-emitting diodes (LEDs) not only increases light extraction, but is also used to control the far-field radiation pattern of the LED. With the proper design light is redirected in useful angles increasing the radiance (light directionality) of the LED; a property useful in étendue limited applications. Data are presented on electrically driven III-Nitride photonic crystal LEDs with various lattice types and constants. Wavelength resolved radiation pattern and power measurement are used to characterize the LEDs. The number of internal optical modes and how they are extracted into air are controlled by the photonic crystal and other device parameters. Modelling is used to identify the scattered modes in the far-field radiation patterns. Photonic crystal LEDs show increased light extraction and radiance compared to non-patterned controls.

12:45 PM
AA5, Microcavity InGaN Light Emitting Diodes with a Single Fabry-Pérot Mode: Jong-Seok Choi; Michael Iza; Gregor Koblmüller; Christophe Hurmi; James Speck; Claude Weisbuch; Evelyn Hu; University of California at Santa Barbara

We report on InGaN microcavity light-emitting diodes supporting a single Fabry-Pérot mode with an effective thickness of 450 nm and a cavity order of 5 at the emission wavelength of 415 nm. The device is a simple asymmetric cavity structure bounded by a highly reflective mirror at the bottom and air at the top. The single Fabry-Pérot mode alters the emission pattern, so that a larger fraction of the generated light can be coupled to the light extraction cone. The device is fabricated by utilizing flip-chip bonding, laser lift-off, dry-etch thinning, mesa formation, and contact deposition processes. Of particular challenge in the processing is the high-precision control of final microcavity thickness. The control of microcavity thickness afforded by our selective dry-etch thinning method can be further complemented by photonic crystal patterning and roughening, leading to highest improvements in light extraction efficiency.

1:00 PM
AA6, GaN Ultraviolet Avalanche Photodiodes Fabricated on Free-Standing Bulk GaN Substrates: Yun Zhang; Dongwonyo Yoo; Jiae-Boum Lim; Jae-Hyun Ryu; Russell Dupuis; Shyh-Chiang Shen; Georgia Institute of Technology

We report a high-performance MOCVD-grown GaN ultraviolet (UV) p-i-n avalanche photodiodes (APD) on bulk GaN substrates. The fabricated APD devices achieved avalanche gain of > 30K and low leakage current density (<10^-7 A/cm) at voltages below 50% of the device avalanche breakdown voltage. Out of more than 40 randomly selected devices tested across an 8 x 8 mm^2 wafer piece, over 50% of them showed repeated avalanche gains greater than 10^4 with device mesa areas up to 4.500 μm^2. To the best of our knowledge, this is the highest linear gain reported to date among III-N-based UV APDs. The robust APD fabrication processing techniques will be suitable for III-N APD sensor array fabrication. Detailed fabrication and device characterization will be presented in the conference.

1:15 PM
AA7, Electro-Optical Intersubband Modulator Based on Electron Tunneling between GaN/AIN Coupled Quantum Wells: Nasrin Khederdin; Laurent Neyou; Houssaine Marchhadani; Maria Tchernycheva; Anatole Lupu; Francois Julien; Paul Crozet; Loïc Meignien; Elias Warde; Giampaiero Pozzovivo; Sebastian Golka; Gottfried Strasser; Fabien Guillot; Eva Monroy; Thilo Remmele; Martin Albrecht; Institut d’Electronique Fondamentale; Technische Universität Wien; CEA-CNRS-UJF; Institut für Kristallzüchtung

Room temperature intersubband electro-absorption modulation in GaN/AIN coupled quantum wells is demonstrated at near-infrared wavelengths, covering the fibre-optics telecommunication wavelength range. The electro-modulation originates from electron tunneling between a wide well (reservoir) and a narrow well separated by an ultrathin (1 nm) AIN barrier. Electro-absorption modulation with opposite sign is observed at λ ≈ 1.2-1.67 μm and λ = 2.1-2.4 μm. Both the intersubband absorption and the modulation spectroscopic measurements are in good agreement with the simulations. The maximum modulation depth with 0.8 V applied across the active region is ≈44 % at λ = 2.2 μm. The -3 dB cut-off frequency limited by the RC time constant is as high as 1.4 GHz for 10x10 μm^2 mesas and could be further improved by reducing the access resistance of the AlGaN contact layers.
Characterization

A Study on the Off-State Breakdown Characteristics for the GaN Buffer Layer of AlGaN/GaN HFET Using Space-Charge-Limited Current Conduction Mechanism: Akhiro Hinoki; Junjiroh Kikawa; Tomoyuki Yamada; Tadayoshi Tsuchiya; Shinichi Kamiya; Masahito Kurouchi; Kenichi Kosaka; Tsutomu Araki; Akira Suzuki; Yasushi Nanashi; 1Ritsumeikan University; 2R&D Association for Future Electron Devices

To improve the performance of AlGaN/GaN HFETs, the reduction in buffer leakage current through the GaN buffer layer is critical, leading to the improvement in off-state breakdown voltage for high-power operation. We have studied on the correlation between the off-state breakdown voltage and the thickness of the GaN layers using space-charge-limited current conduction mechanism. We have found that the thinner GaN layers had larger off-state breakdown voltages and higher trap density. The trap density in the GaN layer was estimated from the trap filled-limit voltage which determined off-state breakdown voltage. TEM studies showed that the thinner GaN layers had higher dislocation densities. These results suggest that the trap state formed by the threading dislocations determines the off-state breakdown voltage of the GaN layer.

Analysis of Buffer-Trapping Effects on Gate Lag, Drain Lag and Current Collapse in AlGaN/GaN HEMTs: Kazushige Horio; Atsushi Nakajima; 1Shibaura Institute of Technology

Although many experimental results are reported on current collapse and slow current transients (gate lag and drain lag) in AlGaN/GaN HEMTs, few theoretical works are performed. Therefore, we have made two-dimensional analysis of AlGaN/GaN HEMTs in which a deep donor and a deep acceptor are considered in the buffer layer, and found that the phenomena observed and current collapse could be reproduced. Particularly, it is shown that gate lag is correlated with relatively high source access resistance of AlGaN/GaN HEMTs, and that drain lag could be a major cause of current collapse. It is also shown that current collapse is more pronounced when the deep-acceptor density is higher and when an off-state drain voltage is higher. It is concluded that to minimize current collapse in AlGaN/GaN HEMTs, an acceptor density in the buffer layer should be made low, although current cutoff behavior may be degraded when the gate length is short.

Anomalous Temperature Dependence of Photoluminescence for InN Grown by MOVPE. Masashi Nakao; Takaaki Shimada; Masaki Wakahisa; Nobuyuki Motej; Akiko Gomyou; Seichirou Mizuno; Takahiro Suzuki; 1Tohoku University; 2NEC Corporation; 3NTT-AT Corporation

Photoluminescence (PL) measurements of MOVPE-grown and air-encapsured InN crystals have been carried out at the temperature between 4 K and 300 K. PL peak wavelengths are located at around 1.52 μm at room temperature. While the PL peak-intensity increases with temperature decrease, the PL peak-wavelength shows red-shift. This tendency of PL peak-wavelength shift is an opposite change as compared with that of other III-V compounds. The observed anomalous PL behavior has precisely been investigated by additional characterization techniques, such as X-ray diffraction method, TEM observation, energy dispersive X-ray spectrometer (EDX), and electron energy-loss spectroscopy (EELS). Lattice structure has been clearly observed on the TEM image for the InN layer. Oxygen incorporation has been found from the EDX analysis. The origin of anomalous PL wavelength shift may come from the difference of thermal expansion in the InN layer. The observed effects are useful to form the crystal structure with temperature-independent emission.

Assessment of the Accuracy of Electrical Channel Temperature Determination in High Power AlGaN/GaN Devices Using Raman Thermography: Richard Simms; James Pomeroy; Martin Kuball; Michael Uren; Trevor Martin; 1University of Bristol; 2QinetiQ Ltd

GaN-based transistor devices are at the forefront of the development of high power, high-frequency micro-electronics. High power dissipation creates self-heating with implications for device degradation. An accurate method of measuring device temperatures is needed to employ effective thermal management in device design. Electrical methods are commonly used to estimate channel temperatures but their accuracy is presently unknown. Micro-Raman thermography can be used to assess the accuracy of electrical temperature measurements. We find that electrical methods underestimate channel temperatures. This is due to the fact that electrical techniques provide an averaged temperature over the entire device. We conclude that electrical techniques can be used to provide qualitative comparisons between different device designs but are unable to provide an accurate estimation of peak temperatures. This has significant implications for reliability studies based on electrical temperature measurements. Micro-Raman spectroscopy can also be used to investigate time-resolved thermal measurements not possible by electrical methods.

Assessment of the Pendeo-Epilaxy Effect on the 2DEG Mobility in III-Nitride HEMT Heterostructures: K. Bulashevich; Sergey Karpo; Yu. Makarov; T. Zhleva; P. Shah; M. Derenge; K. Jones; 1Semiconductor Technology Research, Inc.; 2U.S. Army Research Laboratory

We have examined theoretically the electron scattering related to the interface roughness produced by threading dislocations (TDs) in the channel of an AlGaN/GaN HEMT heterostructure. The considered mechanism is found to limit the low-temperature mobility of electrons at high 2DEG densities, while the Coulomb scattering at charged dislocation core dominates at low 2DEG concentrations. The use of the pendeo-epitaxy enables reduction of both the TD density, typically from ~10^8 cm^-2 to ~5-10^10 cm^-2, and interface roughness, resulting in the mobility improvement. The theoretical calculations of the electron mobility accounting for the above dislocation-mediated scattering mechanisms are compared with available observations. The roughness characteristics and their correlation with the TD density were estimated from the atomic-force microscopy data. The contribution of the scattering mechanisms to the room-temperature mobility is finally estimated to assess the benefit of using the pendeo-epitaxy for the HEMT fabrication.

Carrier Dynamics of InN Thin Films Grown on Si(111): Der-Jun Liang; G-T. Lin; M. E. Lee; L-W. Tu; 1National Sun Yat-sen University, Department of Physics and Center for Nanoscience and Nanotechnology; 2National Kaoshiung Normal University, Department of Physics

The carrier dynamics of InN thin films grown on Si(111) substrates were investigated with the time-resolved photoluminescence (PL) apparatus. The PL rises steeply in the first few ps and saturates later with rise time in the range of 2–10 ps for different excitation intensities when InN thin films were photoexcited with laser pulses of energies of 1.5 eV and 3.0 eV. Carrier temperatures determined from the time-dependent PL spectra reveals that the fast cooling of carrier temperature at the first 10 ps after photoexcitation is the characteristic of energy relaxation of carriers by carrier-LO-phonon interaction. From the carrier cooling curves, we found the effective LO-phonon emission time approaches the theoretical prediction of 23 fs as decreasing the photoexcitation carrier density. This study has verified that the hot phonon effect, instead of plasma screening, plays an important role in reducing the energy loss rate of carriers with excessive energy.

Dynamic Behavior of Metal Contacts Formed on AlGaN/GaN Heterostructure: Hideki Hasegawa; Masamichi Akazawa; 1Hokkaido University

Current collapses in AlGaN/GaN HFETs are due to surface state filling from Schottky gates. However, devices with smaller gate leakage exhibit larger collapse. To resolve this discrepancy, we investigate dynamic behavior of metal contacts on AlGaN/GaN wafers. Circular Schottky or ohmic contacts surrounded by ring-shaped ohmic contacts were used to avoid edge leakage problems. As we reported, Schottky reverse currents decreased by 4-5 orders of magnitude after oxygen gettering which reduces near-surface oxygen

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Electrical Characterization of AlGaN/GaN on Bulk AlN Substrates: William Mitchell; S. Ellhammer; G. Landis; R. Gaska; L. Schowalter; Air Force Research Laboratory; University of Dayton; Sensor Electronic Technology, Inc.; Crystal IS.

The results of an electrical transport study of an AlGaN/GaN heterostructure grown on a bulk AlN substrate are presented. Temperature dependent Hall effect and magnetoresistance measurements were made on the MOCVD/MEMOCVD grown heterostructure. The temperature dependences of the Hall carrier density and mobility were characteristic of a two-dimensional electron gas (2DEG). The Hall carrier density and mobility were roughly 1.19 x 1013 cm-2 and 1100 cm2/Vs at 300 K, and 1.02 x 1013 cm-2 and 5279 cm2/Vs at 10 K. The magnetoresistance measurements revealed the presence of Shubnikov-de Haas (SdH) oscillations. Illumination of the sample resulted in a persistent photocurrent and enhanced the amplitude of the SdH oscillations, indicating an increase in the quantum scattering time. The ratio of the classical to quantum scattering times, τc/τq, was determined to be 4.3, which is within the range of reported values for AlGaN/GaN on other substrates.

High Intensity Red Emission from Eu-Doped GaN Powders: Junxia Shi; M. V. S. Chandrashekar; Jesse Reihzerzer; William Schaff; Jie Lu; Francis Disalvo; Michael Spencer; Cornell University.

An efficient phosphor material was produced with in-situ Eu doping in GaN by a low-cost method. The effect of growth temperature on the optical properties and structure was investigated by photoluminescence. X-ray diffraction and Raman spectroscopy. Band edge and yellow emissions were completely suppressed for the best samples, with a line-width of 2.2 nm. Lattice constants, luminescence intensity and hydrostatic stress increase with Eu incorporation. Analysis of these results indicates that Eu incorporation was substitutional, with a maximum concentration of 0.5 at%. Red luminescence intensity of the best sample has been estimated to be about 8 times higher than previous work.

In-Situ Current-Voltage Characteristics of Swift Heavy Ion Irradiated Au/n-GaN Schottky Diode: Vikas Baranwal; Sandeep Kumar; Avinash C. Pandey; Dinakar Kanjilal; University of Allahabad; Inter-University Accelerator Centre.

In the present work, in situ current-voltage characterization of Au/n-GaN Schottky diode was performed to study the effect of 50 MeV Ni ion irradiation. The Schottky barrier parameters were measured as a function of irradiation fluence. The irradiation fluence was varied from 5x1010 ions-cm2 to 5x1011 ions-cm2. The ideality factor for pristine diode was 4.01, which decreases to 2.2 after the irradiation with a fluence of 1x1010 ions-cm2. At a fluence value of 5x1010 ions-cm2 the value of ideality factor becomes 1.7. The Schottky barrier height increases from 1.05 eV for pristine diode to 1.08 eV at a fluence of 5x1010 ions-cm2. The values of Schottky barrier height are respectively 1.03, 1.02, 1.01 with the fluence of 1x1010 ions-cm2, 1x1010 ions-cm2, 5x1011 ions-cm2. These results are interpreted on the basis of energy loss mechanisms and dynamic annealing due to swift heavy ion irradiation at the metal-semiconductor interface.

Light Emission Characteristics of GaN HEMTs and Its Implications on Device Operations: Hsiang Chew; Guann-Pyng Li; University of California, Irvine.

The GaN HEMTs are promising for high power and high frequency applications. However, defects induced during material growth and device fabrication imposed constraints on the device performance. A hyperspectrum imaging measurement technique to characterize the electroluminescence from GaN HEMTs is developed for real time in-situ monitoring of defects in devices. While the light emission in on-state operation is continuous throughout the entire gate width, that in off-state has distinct emission spots. Among those spots, they show two separate wavelength dependences. The first type has the same spectrum shape as the one observed at on-state and shows a minor dependence on electric filed. The second type depicts a similar characteristic as the yellow band electroluminescence defect in the GaN and shows a stronger dependence on the electric field than that of the first type of emission spot. This technique reveals unique properties of possible material defects and device imperfection.

Low On-Resistance AlGaN/GaN HEMTs by Reducing Gate Length and Source-Gate Length: Toshibide Idea; National Institute of Advanced Industrial Science and Technology (AIST).

In this study, the AlGaN/GaN HEMT characteristics were improved by reducing both LG and LSG, and the low specific on-resistance was achieved. The gate length LG is varied from 0.1 to 6.0 µm. The source-gate spacing LSG is varied from 0.5 to 1.1 µm. The maximum transconductance gmmax is improved by reducing LG and LSG. The gmmax is proportional to (LG+LSG)^(-0.25). The reduction of LSG is as effective as the reduction of LG for the enhancement of gmmax. The highest gmmax is 280 mS/mm at a LG of 0.1 µm and a LSG of 0.5 µm. At a LG of 0.1 µm, a LSG of 0.5 µm and a drain-gate spacing of 1.6 µm, the specific on-resistance and breakdown voltage are 0.1 mOhm-cm^-2 and 56 V, respectively. This result shows better specific on-resistance than the numerical calculation of the lateral GaN FETs.

Luminescence and Vibrational Properties of Erbium-Implanted Nanoporous GaN: Chew Beng Soh; Soo Jin Chua; Si Hui Sim; Sudhiranjan Tripathy; E. Alves; Haryono Hartono; Institute of Materials Research and Engineering; National University of Singapore; H 16; Singapore-MIT Alliance, National University of Singapore.

Implantation of Erbium (Er) into GaN is useful in creating selected areas to emit at the green, yellow and infrared wavelengths. Enhanced Erbium activation is obtained when Erbium is implanted into porous GaN formed by electrochemical etching than into as-grown GaN. This is due to the increase in surface areas for light extraction and the availability of more free surfaces to accommodate strain when it is annealed. Furnace annealing at 1100 deg for 30 mins in nitrogen gives rise to higher band-edge photoluminescence intensity. Apart from the host GaN phonon modes, we have also observed disorder-induced lattice vibrations at 170, 200 and 350-365 cm^-1 from Er-implanted porous GaN. The E2 (high) mode of GaN also shifts towards higher energy at higher annealing temperatures, indicative of more Erbium occupying the VGa site (ionic radii of Er > Ga) and hence increasing the compressive stress in the GaN crystal lattice.

Micro-Raman Analysis on InN Layers Grown by HPCVD: Rommy Kirste; Mustafa Alevi; Nikolaus Dietz; Axel Hoffmann; Technical University Berlin; Georgia State University.

Embedding InN and indium-rich group III-nitride alloys into wide band gap Ga-xAlxN group III-nitrides is essential for a large number of envisioned device structures, ranging from spectral tailored displays, white LED’s, or detectors. To stabilize InN at processing conditions used for GaN, a novel high-pressure chemical vapor deposition (HPCVD) system was developed enabling the growth of single-crystalline InN layers at growth temperatures at 850°C for reactor pressures around 15 bar. Raman spectra were taken on samples grown with HPCVD at different ammonia/TMI ratios and on different substrates. According to the FWHM’s of the E2 (high) mode, both the ammonia/TMI ratio as well as the substrate have a strong influence on the crystalline quality of the grown InN layers. Spatially resolved Raman measurement across cracks in InN layers show different degree of strain relaxations at the edges and across of such cracks.
Microscopic Thermal Analysis of AlGaN/GaN HFETs Using Micro-Raman Spectroscopy and Electro-Thermal Simulation: Kenichi Kosaka1; Tatsuya Fujishima2; Kaoru Inoue1; Akhiro Hinoki1; Tomoyuki Yamada1; Tadayoshi Tsuchiya3; Junjiroh Kikawa1; Shimichi Kamiyai1; Akira Suzuki1; Tutomu Araki1; Yasushi Nanishi1; Ritsumeikan University; Advanced HF Device R&D Association for Future Electron Devices; Ritsumeikan University and Advanced HF Device R&D Center, R&D Association for Future Electron Devices

We report on investigation of self-heating effects in AlGaN/GaN HFETs using micro-Raman spectroscopy and numerical simulations. Both AlGaN/GaN HFETs on sapphire and SiC substrates were studied using micro-Raman for 2D (two-dimensional) mapping. In the numerical simulations, we used a temperature-dependent thermal conductivity for each constituent material. Good agreements between the simulated and measured surface temperature distributions have been obtained, which supports the validity of simulation models. The measured infinitesimal thermal temperature distribution for HFETs on SiC substrates was found to have a peakier than that on sapphire substrates. In addition, the region around the gate edge on the drain side usually showed a maximum temperature for the devices operating at drain voltages less than about 40 V, but this maximum temperature region shifted toward the drain side when the drain voltage was further increased. These results confirm and study usefulness of micro-Raman spectroscopy for high-resolution temperature measurements of power devices.

Negative Differential Resistance in GaN Lateral Structure Schottky Diodes: Wenbao Liu; 1Institute of Semiconductors Chinese Academy of Sciences

Lateral structure Schottky diodes were fabricated on unintentional doped GaN films grown on (001) sapphire by metalorganic chemical vapor deposition. With increasing forward biased voltage the current has been observed to decrease slightly in current-voltage measurements. For some diodes this negative differential resistance phenomenon can repeat for many times. Two reasons are supposed. One may lie in the Shirley effect. In addition of the bad thermal conductivity of GaN Schottky diodes that heat themselves under big voltage and current, consequently the mobility of electrons decreases with increasing temperature of devices. As a result the density of current decreases and negative differential resistance appears. The mechanism behind is under further research.

SIMS and Raman Studies of Mg-Doped InN: Valery Davydov1; Albert Klochikhin2; Alexander Smirnov1; Olga Chikavolu-Luzina1; Mikhail Smirnov1; Hai Lu3; William Schaff1; Hong-Mao Lee1; Hon-Way Lin1; Shangyr Gwo2; Joffe Physico-technical Institute; Saint-Petersburg State University, Fock Institute of Physics; Cornell University; National Tsing-Hua University

We present results of experimental and theoretical studies of lattice dynamics of Mg-doped InN which is promising for p-type doping. The samples studied were grown by PAMBE on sapphire (001) and silicon (111) substrates. The Mg concentrations ranged from N_{Mg} = 1.6 \times 10^{10} to 2.3 \times 10^{11} cm^{-2}, as determined by SIMS measurements. It has been found that the normalized intensity of LO-phonon Raman band strongly correlates with the Mg concentration estimated from SIMS data. Moreover, the Raman spectra appear to be identical for the samples grown on different substrates but having similar Mg contents. These findings indicate that Raman spectroscopy is a promising technique for quantitative estimation of Mg content in Mg-doped InN samples. Lattice dynamics of hexagonal InN involving substitutional impurities and vacancies was calculated in the framework of cluster approach, and energy positions of Mg local vibration modes in InN were predicted. They were found to be consistent with experimental findings.

The Effects of Interface States on the C-V Behavior of Insulated Gates on AlGaN/GaN Heterostructures: Marcin Miezik1; Chihoko Mizue1; Tamotsu Hashizume1; 1Hokkaido University

The impact of states at the insulator/AlGaN interface on capacitance-voltage (C-V) characteristics of a metal/insulator/AlGaN/GaN structure was examined rigorously for the first time using a numerical solver of Poisson equation taking into account the electron emission rate from the interface states. A parallel shift of the theoretical C-V curves instead of typical change in their slope was found in the SiN/Al_{23}Ga_{77}N/GaN structure at 300°C during increasing the SiN/AlGaN interface state density, D_{it}. This behavior was explained by the position of Fermi level at the SiN/AlGaN interface below the valence band maximum of AlGaN when the gate bias was near the threshold voltage. Finally, the experimental C-V characteristics measured at room temperature and 300°C from a SiN/AlGaN/GaN structure were analyzed and a part of D_{it} was extracted. A relatively low D_{it} (\sim 10^{11} eV^{-1}cm^{2}) in the upper bandgap indicates that the SiN gate insulator is applicable to high-temperature and high-power AlGaN/GaN-based devices.

Materials Integration

Atomic and Electronic Structure of the Cleaved 6H-Sic(11-20) Surface: Marco Bertelli1; Jan Homoth1; Martin Wenderoth1; Angela Rizzi1; Rainer Ulbrich1; Maria Clelia Righi2; Carlo Bertoni1; Alessandra Catellani2; 1Georg-August-University of Goettingen; 2University of Modena and Reggio Emilia; 2CNR-IMEM

The efficiency of radiative recombination in GaN-based optical devices is improved for structures grown in a direction perpendicular to non-polar planes. We present a combined cross-section STM and scanning tunneling spectroscopy (STS) and ab initio simulations study of the non-polar (11-20) cleaved surface of 6H-Sic. The experiments show an unstructured surface in agreement with theory. Upon truncation, two surface bands appear inside the semiconductor band gap; one empty band localized on the Si atoms and one filled band on the C atoms. According to the STS experiments on n-doped samples, the Fermi energy is pinned at the surface inside the band gap. By comparison of STM filled and empty states topographies we propose that the fresh cleaved surface the Fermi level lies at the bottom of the Si-like band. The calculated STM images reproduce the experimental contrast of the 6H stacking sequence and its bias dependence very well.

Band Structure and Effective Mass of InN under Pressure: Iza Goreczyca1; Leslaw Dmowski1; Jerry Lesiewicz2; Tadeusz Suski2; Niels Christensen1; Axel Svan1; Chad Gallina1; Gregor Kohlmuller1; James Speck1; 1Institute of High Pressure Physics; 2Department of Physics and Astronomy, University of Arkansas; 3Materials Department, University of California

Calculations of the electronic band structure and effective mass of InN are performed within the density functional theory by means of the linear muffin-tin-orbital method with adjusted band gaps. The results show a pronounced non-parabolicity of the conduction band. Calculated variations of the optical gap and electron effective mass with free electron concentration are presented and compared to available experimental data. Pressure effects are studied. Both the fundamental band gap and the electron effective mass increase with hydrostatic pressure, but due to the non-parabolic character of the conduction band of InN the pressure coefficient of the effective mass decreases with electron concentration. Experimental verification of this behavior has been performed on three n-type samples of InN with different electron concentrations. The measurements and calculations agree in the description of the dependence of effective mass and its pressure coefficient on electron concentration.

Bulk and Surface Electron-Induced Infrared Magnetoresponse in InN: A Possible Evidence for a New Defect-Related Doping Mechanism: Tino Hofmann1; H. Lu2; W. Schaff1; V. Darakchieva1; M. Schubert1; 1University of Nebraska-Lincoln; 2Cornell University; 3Linköping University

Measurements of free electron induced infrared magnetoresponse birefringence in naturally-doped wurtzite-structure InN thin films by generalized ellipsometry reveal that both the surface and the interior (bulk) free electron densities decrease with power-law dependencies on the film thickness. We discover a significant deviation between the bulk electron and dislocation densities. We attribute this difference to the existence of surface defects with activation mechanism different from bulk dislocations, and which identifies the possible origin of the so far persistent natural n-type conductivity in InN. Our non-contact measurements may provide the missing information to understand the physical origin of the strong electron accumulation at the

**Technical Program**

**Characteristics of InGaN/GaN Films Grown on Hemispherical Patterned Sapphire (HPS): Jae-Hoon Lee**

- Samsung Electro-Mechanics


**Surface pattern of the HPS hemispherical patterned sapphire substrate.**

**Circular Photogalvanic Effect of the Two-Dimensional Electron Gas in AlxGa1-xN/GaN Heterostructures under Uniaxial Strain:** W.X. He1; B. Shen2; Y.Q. Tang1; Ning Tang1; F.J. Xu1; Z.X. Qin1; G.Y. Zhang1; Y. Chen1; C. Tang1; Z. Wang1; State Key Laboratory of Artificial Microstructure and Mesoscopic Physics, School of Physics, Peking University; Laboratory of Semiconductor Materials Science, Institute of Semiconductors, Chinese Academy of Sciences.

The circular photogalvanic effect (CPGE) based on the spin of the two-dimensional electron gas (2DEG) in Al0.25Ga0.75N/GaN heterostructures has been investigated using the infrared radiation under the uniaxial strain. The photogalvanic current original from the CPGE is observed up to 10-2 nA at room temperature, which has the notable change under the uniaxial strain. The amplitude of the photogalvanic current increases linearly by 20% with the augment of the strain ranging from 10-4 to 10-3, indicating that the k-linear spin splitting (SIA) of the subbands in the triangular quantum well at Al0.25Ga0.75N/GaN heterointerfaces is enhanced owing to the additional outer strain. Based on the experimental results, it is suggested that the Rashba constant in AlxGa1-xN/GaN heterostructures can be modulated through the outer strain.

**Comparison of Transition Metal Incorporation and Phase Segregation in MOCVD-Grown Ga(Fe,Mn)N:** Matthew Kane1; Shalini Gupta2; William Fenwick3; Man Han4; Z. Zhang5; Ian Ferguson6; Georgia Institute of Technology

Nitride-based dilute magnetic semiconductors have been of recent interest in spintronics. It is still controversial as to whether the observed room temperature magnetic hysteresis is due to transition metal agglomeration or formation of a midgap impurity band. The comparison of Mn and Fe incorporation in GaN allows for a simultaneous evaluation of these models. This study explores the magnetic properties of Ga1-xMnxN and Ga1-xFexN grown by MOCVD. Magnetic hysteresis is observed at room temperature, even at dilute alloying concentrations. Competing contributions from isolated d5 and d4d ions and a transition metal-rich phase dominate the magnetic signature. Conversion of the trivalent to divalent transition metal states has been confirmed via optical transmission. A distinct splitting is observed in the ZFC/FC magnetization curves with silicon codoping, consistent with an array of nanoscale clusters. The Ga1-xFe1-xN samples exhibited a degraded crystal quality relative to the Ga1-xMnxN as evidenced by structural studies.

**Crystal Growth of InN by the Use of Field Effect MOVCD:** Takashi Inushima1; Masaki Higo1; Ramkrishna Biswas1; Tokai University

Thermodynamically stable wurtzite structure InN has a polar axis parallel to the c-direction of the crystal lattice. Electrostatically, such macroscopic lattice polarization can be controlled by external field as is in conventional ferroelectric materials. In this experiment we controlled the polarity of InN by the use of field effect MOVCD, where electric field was applied along the c-direction of InN, the growth direction. We set two electrodes in the horizontal MOVCD system, SUS electrode was placed 3 mm above the other electrode Mo susceptor. The effect of the electric field was evaluated by the rocking curves of InN(0002) Bragg spots, Raman spectra, band gap energy and superconductivity. The electric filed improved the crystal quality when it was applied both during crystal growth and during cooling down. When the field of 1 kV/cm was applied from the substrate to SUS electrode, enhancing N-surface growth, the narrowest rocking curve was obtained.

**Development of a Procedure for MOVPE Growth of GaN on ZnO-Buffered C-Sapphire Substrates Followed by Chemical Lift-off of the GaN:** Abdallah Ougazzaden1; Dave Roger2; Manijhi Razeghi3; Georgia Institute of Technology; Nanovation SARL; Northwestern University

The development of GaN devices has been hampered by the lack of suitable transparent, lattice- and thermal-matching substrates since good quality single crystal GaN substrates have not been widely available at acceptable cost levels. Hence, GaN has been grown on a variety of substrates. Most of the work has been done using c-sapphire and 6H-SiC substrates. Another alternative and promising substrate for GaN epilayers is Zinc Oxide (ZnO). It has the same wurtzite structure than GaN and a small lattice mismatch (2%). Furthermore, c-axis GaN/ZnO shows a much-reduced mismatch in thermal expansion coefficient compared with GaN/SiC or GaN/c-sapphire. In this paper, we present the development of an MOVPE growth procedure which yields high quality GaN on ZnO. SEM and AFM confirmed homogeneous ZnO and GaN films. XRD, Raman and PL studies confirmed that the layers were well-cristallised. Auger spectroscopy showed no evidence of Zn or Al at the film surface.

**Electric Field Effect Free Characteristics of Ultra-Thin In-Rich InxGa1-xN/GaN Multiple Quantum Well Light Emitting Diodes:** Hee Jin Kim1; Soon-Yong Kwon1; Pilkyung Moon1; Suk Choi1; Yong Seon Jeon1; Sung Hyun Park1; Seung-Hwan Park2; Taehoon Chung3; Jong Hyeob Baek3; Yoon Soo Park4; Euijoon Yoon5; Seoul National University; Catholic University of Daegu; Korea Photonics Technology Institute; Rensselaer Polytechnic Institute

We confirmed electric field effect free property in ultra-thin In-rich (UTIR) InxGa1-xN/GaN multiple quantum well (MQW) by fabrication of light emitting diode (LED) device. The current-voltage characteristic of this LED showed rectifying behavior with a forward voltage of 3.4 V at 20 mA. Electroluminescence (EL) peak from UTIR InGaN/GaN MQW LED was observed at 393 nm with a narrow full width at half maximum of 20 nm. Electric field effect free characteristics in UTIR InGaN/GaN MQW LEDs were revealed by negligible EL peak shift with increasing injection current as well as the energy band calculation using kp method. This electric field free UTIR InGaN/GaN MQW LEDs is expected to be a new near-ultraviolet source.
Electrical and Optical Properties of Thick Highly Doped P-Type GaN Layers Grown by HVPE: Alexander Usikov; Oleg Kovalenko; Vitaly Soukhoveev; Vladimir Vantsov; Alexander Syrkin; Vladimir Dmitriev; Alexey Nikiforov; Siddarth Sundaresan; Stojan Jeliazkov; Albert Davydov; 1Technologies and Devices International, Inc.; 2Boston University; 3George Mason University; 4National Institute of Standards and Technology

We report on p-type GaN layers and AlGaN/GaN heterostructures grown by hydride vapor phase epitaxy. Highly doped p-GaN thick layers and structures with low electrical resistivity are attractive substrates for novel GaN-based devices. As grown GaN layers had p-type conductivity with concentration N_A-N_D up to 1x10^{20} cm^{-3} and 8x10^{17} cm^{-3} for Mg-doped and Zn-doped layers, respectively. Acceptor atom concentration was varied from 10^{17} to 10^{20} cm^{-3}; Hydrogen concentration was about 10 times less than that for Mg, which may explain effective p-type doping for as-grown GaN layers. Electrical conductivity at 300 K for p-GaN ranged from 1 to 50 Ohm^{-1} cm^{-1} depending on doping level. Micro cathodo luminescence revealed a columnar-like structure of the GaN layers with a non-uniform distribution of defects. In areas relatively unexposed to electrons, a survey of core character, diameter and depth into the layer suggests that a similar process occurs by post-growth annealing, i.e. due to point defects mobile at the growth temperature. The implications of these results for understanding dislocation core structures are assessed.

Electrical Conduction in Cubic GaN Films Grown on GaAs(001) by RF-MBE: Masatoshi Kohno; Teruyuki Nakamura; Takahiro Kataoka; Ryuji Katayama; Kentaro Onabe; 1University of Tokyo

The electrical conduction property in c-GaN films grown on GaAs(001) by RF-MBE has been studied in relation with the amount of the hexagonal phase inclusion, or cubic phase purity. In a high-phase-purity (93%) film, the electron concentration and mobility at 300 K are typically 8x10^{19} cm^{-3} and 110 cm^{2}/Vs, respectively. It is known that a parallel conduction is occurring in which the high mobility region somewhere away from the hetero-interface dominates the conduction at higher currents. In a lower-phase-purity (75%) film, it is indicated that the low mobility region extends over the larger region of the film. Above the cubic phase purity of 90%, the electron concentration rapidly decreases and the mobility rapidly increases by one or two orders of magnitude, suggesting that the stacking faults are the major source of the carrier electrons and causing the scattering centers responsible for the low mobility region.

Electrical Properties and Optical Absorption in Periodic InN:In Structures: Tatiana Komissarova; Dmitry Plotnikov; Valentine Imerik; Tatiana Shubina; Andrey Mizerov; Alexey Semenov; Sergey Ivanov; Ludmila Ryabova; Dmitry Khokhlov; 1Moscow State University; 2Institute of Physico-Technical Institute, Russian Academy of Sciences

Metallic In nanoclusters may form spontaneously in InN epitaxial films during growth process. We performed electro-physical and optical absorption measurements in conventional InN epilayers and intentionally formed InN in composite periodical structures (PS). It was found that the intentional introduction of In metal cluster sheets in InN does not change noticeably the carrier concentration and mobility of composite InN/PS with respect to pure InN films, while absorption spectra in PS are significantly modified. The absorption spectra have a complicated shape, which may result from superposition of Mie resonances and absorption in the semiconductor matrix. The principal absorption edge is shifted to higher energies with increasing In amount in the indium inserts. This effect is discussed in terms of variation of the Mie resonance energy in the clusters and depletion of the medium by indium due to the Lifshitz-Slezov mechanism. The relevant uncertainty in the optical gap of InN is analyzed.

Electron Density and Electron Scattering Processes of InN/GaN Heterostructures: Yoshitomo Ishihara; Masayuki Fujiwara; Xinqiang Wang; Song-Bek Che; Akihiko Yoshikawa; Chiba University

We analyzed the infrared reflectance spectra of InN down to 200 cm^{-1}. This measurement removed the barrier for the elucidation of electronic properties inside bulk region: the barrier by the surface and interface electron accumulation. It was found that the surface electrons had the mobility of the order of 10 cm^{2}/Vs or less, and that the electrons accumulated around the InN/GaN interface had the density of 10^{17} cm^{-2}. The value inside the bulk region was down to 3x10^{10} cm^{-2} even though the average one of all the area was nearly 10^{18} cm^{-2}. These electrons showed the remarkable E_{1}(LO) phonon – plasmon coupling (LOPC) feature just around the energy level anti-crossing region of two LOPC modes. The obtained electron scattering rate for E_1 symmetry was smaller than 1 cm^{-1}, but it is indicated that for A_1 one reported by another group. The reduction of edge type dislocation density is important for the improvement of the electron scattering property.

Electron Irradiation and the Equilibrium of Open Core Dislocations in Gallium Nitride: Michael Hawridge; David Cherns; 2Lawrence Berkeley National Laboratory; 3University of Bristol

Under electron irradiation, nanopipes in GaN are found to evolve into the so-called bamboo structure and eventually into a chain of pinholes [Pailloux et al., Applied Physics Letters 86, 131908 (2005)]. Here, the driving mechanism for this morphological evolution is examined using transmission and scanning transmission electron microscopy studies of undoped GaN grown by hydride vapor phase epitaxy. Irradiation at varying beam energies shows that morphological evolution occurs below the threshold for direct knock-on damage, and that pinholes migrate towards the beam. It is proposed that these observations can be explained by the stimulated diffusion of point defects. In areas relatively unexposed to electrons, a survey of core character, diameter and depth into the layer suggests that a similar process occurs by post-growth annealing, i.e. due to point defects mobile at the growth temperature. The implications of these results for understanding dislocation core structures are assessed.

Epitaxy of InN/In2O3 Heterostructures: Chunyu Wang; Vadim Lebedev; Volker Cimalla; Thomas Kups; Gernot Ecke; Oliver Ambacher; J. G. Lozano; Francisco M. Morales; R. Garcia; D. Gonzalez; 1TU Ilmenau; 2Universidad de Cádiz

The heterosystem InN/In2O3 is very attractive for two reasons: first, by the use of In2O3 serving as a template, hexagonal(h)- and cubic(c)-phases of InN with an improved structural quality can be obtained which have the highest electron mobility among III-nitrides; second, high-quality c-InN films having a larger band gap (~3.7 eV) than InN can be deposited on InN which are excellent candidates as gate oxide material for InN based high-frequency field effect transistors. In this work, the epitaxial growth of the heterosystems InN/In2O3 as well as In2O3/InN was investigated. High-quality c-InN(001) was deposited on (100)In2O3 template with a reticular misfit of 1.6%, while single crystalline c-In2O3(111) was epitaxially grown on h-InN(0001) with an effective lattice mismatch of 2.4%. The epitaxial relationship of the heterosystem In2O3/InN was determined as In2O3[111]// InN[0001] and In2O3[10-11]/InN[11-20]. Phenomenological models for the growth and interfaces of the heterosystems are proposed.

Eu^{2+} Doped GaN Thin Films Grown on Sapphire by Pulsed Laser Deposition: Nestor Perea-Lopez; Jonathan Tao; Jan Talbot; Joanna McKittrick; Madis Raukas; Joe Laski; Kailash Mishra; Gustavo Hirit; 1University of California, San Diego; 2O’sram Sylvania; Centro de Ciencias de la Materia Condensada-Universidad Nacional Autónoma de México

By means of pulsed laser deposition, Eu^{2+} doped GaN thin films were grown on sapphire. The PLD target was formed by pressing GaN:Eu_{powder synthesized by dissolving stoichiometric amounts of Ga_{2}O_{3} and Eu_{2}O_{3} in nitric acid which produces Ga_{4-x}Eu_{x}(NO_{3})_{3}. Next, the nitrates were oxidized in a tubular furnace with O_{2} flow forming Ga_{4-x}Eu_{x}O_{3}. Finally, the oxide powder was flushed with anhydrous ammonia to produce the desired nitride product: Ga_{4-x}Eu_{x}N. The growth was done in a stainless steel vacuum chamber partially filled with N_{2} (400 mTorr). For the deposit, the 3rd harmonic of a Nd:YAG laser (λ=355nm) was focused on the surface of the target. After deposition, annealing in NH_{3} was required to have films with pure GaN hexagonal phase. The luminescence of the film was characterized by photo and cathodoluminescence. In addition, their chemical and structural properties were analyzed with SEM, EDS, XRD, AES and ESCA.
Technical Program

Experimental and Ab-Initio Studies of Temperature Dependent InN Decomposition in Various Ambient: Rie Togashi; Tomoki Koshiba; Yuuki Nishizawa; Hitoshi Murakami; Yoshio Kumagai; Akimori Kikutttu; Tokyo University of Agriculture and Technology

Thermal stability and decomposition behaviors of InN films in various ambient are quite important issues not only for achieving InN growth with high-quality and high-growth-rates but also for revealing the growth mechanism of III-N semiconductors. In this paper, decomposition of N-polarity InN films grown on (0001) sapphire substrates by HVPE are investigated in various ambient and at various temperatures by both experimental analysis and first-principles calculation. It was found that decomposition of an InN film in flowing N2 starts to occur at about 600°C, whereas that in flowing H2 becomes significant at 400°C leaving In droplets on the surface as well as decrease of the film thickness. This fact means that the use of an inert carrier gas is favorable for InN growth. The decomposition mechanism including its activation energy was compared among InN, GaN, and AlN, that was also well explained by first-principles calculation.

Growth and Characterization of InCrN and (In,Ga,Cr)N Diluted Magnetic Semiconductors: Shigeyama Kima; Shiuchi Emura; Yuki Hiromura; Yui Kai Zhou; Shigezako Hasegawa; Hajime Asahi; Osaka University

Diluted magnetic semiconductors (DMSs) are attractive materials for potential applications in spin-detective photonic and electronic devices. It is reported that some III-nitride based DMSs show room-temperature ferromagnetism. GaCrN and InCrN are ones such materials. It is considered that relative location between band gap and Cr d level in DMSs is related to the mechanism of their ferromagnetism. Therefore, it is expected to enable to control ferromagnetic ordering of (In,Ga,Cr)N system by tuning band gap energy with changing the contents of In and Ga. GaCrN, InCrN and (In,Ga,Cr)N films were synthesized on GaN (0001) templates at 350°C using plasma-assisted molecular beam epitaxy. X-ray diffraction (XRD) and 2θ curve shows that lattice constant of (In,Ga,Cr)N is systematically shifted with In and Ga content following Vegard’s law. Ferromagnetic behavior is observed at room temperature for Cr doped Inx,Gax,N sample grown with a Cr c cell temperature of 910°C.

Growth and Characterization of InN Thin Film by Metal-Organic Vapor Phase Epitaxy (MOVPE) on Different Buffers: Pet-Hwa Chang; C.A. Chang; N.C. Chen; H.C. Peng; D.C. Lin; Chang-Gung University; Taichung University

Superconductivity and transport characteristics of In- and N-polarity InN thin films on sapphire substrate were presented in this study. Single-crystalline In- and N-polarity InN films were obtained with nitridation, AlN, In0.22Ga0.78N, In0.3Ga0.7N, GaN as buffer layer by metal-organic vapor phase epitaxy (MOVPE) respectively. The influence of buffers on the growth of InN film was characterized by their transport properties, XRD, PL (Photoluminescence), AFM and SEM. Charge accumulation of the In- and N-polarity InN films were studied The influence of InN polarity on the superconductivity and transport property was also investigated in this work. Details are discussed in the paper.

Growth of High Purity Cubic InN Films on MgO (100) Substrates: Reni Ohtaa; Kazuya Mitamura; Satoshi Kawano; Jitsuo Ohtaa; Hiroshi Fujioka; Masaharu Oshima1; 1The University of Tokyo

We have grown cubic InN films on MgO (100) substrates by pulsed laser deposition (PLD) and have investigated their structural properties. Direct growth of InN on MgO (100) substrates results in formation of hexagonal c-plane InN films. However, the use of cubic GaN (0001) buffer layers, which should alleviate the lattice mismatch between InN and MgO, enables us to grow high quality cubic InN (100). Careful data interpretation for EBSD phase mapping and x-ray reciprocal space mapping has led us to conclude that the phase purity of the cubic InN film grown with the cubic GaN buffer layer is as high as 99%. This successful crystal growth of high purity cubic InN by PLD can be attributed to the enhanced surface migration of In atoms, which is important to convey the cubic arrangement of the atoms in the MgO substrates to the InN films.

Growth of High Purity Un-Doped and Mg-Doped GaN Thick Films by CVD: Rafael Garcia1; Alan Thomas1; Fernando Ponce1; 1Arizona State University; Rogers Corporation

High-quality doped and undoped GaN thick films have been grown on different substrates by reacting Ga and Ga-Mg alloys with ammonium chloride using ammonia as a carrier gas in a horizontal quartz tube reactor at 900°C. The undoped films were grown by a two-step chemical vapor deposition process using Ga and NH4Cl as starting reagents. The doped films were deposited by the same method plus an intermediate step, making a diluted alloy Ga-Mg before the CVD process. These films consist of self-assembled micro-columns that coalesce to form high density thick layers. They have a wurztite structure and exhibit strong room-temperature luminescence with the characteristic GaN band edge as well as the Mg-related emissions for the doped films. The optoelectronic properties of these films are comparable to the GaN thin films grown epitaxially with other techniques. This growth technique can be used for inexpensive, large area electroluminescent devices.

Growth of High Quality InN on Production Style PA-MBE System: Julian Gherasoiu; Mark O’Steere; Tom Bird; Dave Gotthold; A. Chandolou; D. Y. Song; S. X. Xu; M. Holze; S. A. Nikishin; William Schaff; Veeco Instruments Inc.; Nano Tech Center at Texas Tech University; Cornell University

We have demonstrated step-flow growth mode of InN, with monolayer height terrace steps (0.281nm), using a production-style PA-MBE system, GEN200. MOCVD GaN templates have been overgrown in a two-step process. The surface morphology exhibits the step-flow features on relatively large areas and the RMS roughness over an area of 5 x 5 μm is 1.4nm. We also investigated the consequences of In droplets formation during the growth, and we have found that the VLS growth mechanism generates defective layer areas underneath the droplets. The Hall mobility of 1μm thick InN layers gained in such step-flow mode is slightly higher than 1400 cm²/Vs while for other growth conditions we have obtained mobility as high as 1904 cm²/Vs at room temperature. The samples exhibit high intensity PL spectra with a band edge absorption (~0.64eV) that follows the predictions of Moss-Burstein effect.

Growth of Nonpolar A-Plane GaN on R-Plane Sapphire: Matthias Wienenke; Armin Dugda; Jürgen Bläsiing; Andre Krtschil; Hartmut Witte; Thomas Hempel; Peter Veit; Jürgen Christen; Alois Krost; Otto-von-Guericke-University Magdeburg; EMB/IEP

Nonpolar a-plane GaN films were grown on r-plane sapphire by metal-organic vapor phase epitaxy. By varying the growth-temperature and the thickness of an in-situ deposited SiN nanomask the influence on the surface morphology, the electrical and micro structural properties were studied. Optical Nomarski microscopy images showed a decrease of pit density with decreasing growth temperature and thickness of the SiN nanomask, respectively. Additionally, the surfaces were studied by scanning electron microscopy and atomic force microscopy. Investigation of the grown films by high resolution X-ray diffraction revealed anisotropic micro structural properties. In addition the growth defects of the GaN films were studied by transmission electron microscopy. Electrical properties were studied by Hall effect and CV measurements. An enhanced electron concentration is found at the substrate/GaN interface when using a SiN mask. Furthermore, in samples without a mask the high resistivity is controlled by electrically active defects.

High-Temperature Growth of AlN in a Production Scale 11x2” MOVPE Reactor: Frank Brunner1; Harry Potzmann1; Michael Heukin; Arne Knauer1; Markus Weiers1; Michael Kneissl1; Ferdinand-Brand-Institut für Höchstfrequenztechnik (FBI) im FVB e.V.; AIXTRON AG

We report on the growth of high quality AlN films on sapphire by MOVPE in an AIX2400G-HT planetary reactor. Specific reactor hardware modifications were conducted to facilitate growth temperatures up to 1600°C and to obtain reduced parasitic gas phase reactions. Growth was optimized regarding growth rates, surface morphology as well as optical and structural properties of the AlN layers on sapphire. With increasing growth temperature we observe a transition from a 3-dimensional columnar-
like AlN surface to a feature-less smooth morphology. The impact of the growth parameters and the re-designed reactor inlet configuration on the AlN properties has been investigated in detail by X-ray diffraction, AFM, photoluminescence and SIMS. The effects of residual reactor contaminants (e.g. oxygen) on the growth behaviour and the role of Ga as a possible surfactant during AlN growth will be discussed.

Hydrostatic Pressure Coefficient of Photoluminescence in InGaN: From InN to GaN: Gigi Fransen; Tadeusz Suski; Agata Kaminska; Izabela Gorczyca; Andrzej Suchocki; H. Lu; W. J. Schaft; M. Kurouchi; Y. Nanishi; E. Iliopoulos; A. Georgakilas; Polish Academy of Science, Institute of High Pressures Physics; Polish Academy of Science, Institute of Physics; Cornell University, Department of Electrical and Computer Engineering; Ritsumeikan University, Department of Photonics, School of Science and Engineering; FORTH, Institute of Electronic Structure and Lasers

The microscopic origin of (i) very efficient light emission from InGaN structures with x ≈ 0.1–0.2 and (ii) a strong reduction of this efficiency for x > 20–30% are much debated. In order to understand these phenomena, accurate knowledge of the band structure of InGaN alloys is essential. Hydrostatic pressure measurements are useful for the exploration of the band structure. In this work, we present a study of the photoluminescence (PL) pressure coefficient dE/dP of InGaN alloys, which is closely related to the band gap pressure coefficient dEg/dP. Evolution of dE/dP is studied in the entire range of ternary alloys from GaN to InN. Basing on these findings as well as on first-principle calculations we discuss the possible origin of the evolution of the band gap with In content and pressure. Special attention is paid to the large bowing in the region with low In content.

Increase in Luminescence Efficiency of GaPN Epilayers Grown by Migration-Enhanced Epitaxy: Kazuyuki Umeno; Yuzo Furukawa; Ryo suke Noma; Hiroo Yonezu; Akhiro Wakahara; Kunio Itoh; Toyohashi University of Technology; Tsuyama National College of Technology

Dilute nitrides, such as GaPN alloys, have received much attention for Si-based monolithic optoelectronic integrated circuits. However, GaPN layers grown by molecular-beam epitaxy (MBE) showed remarkable thermal quenching in photoluminescence (PL) intensity caused by non-radiative recombination centers. In this work, migration-enhanced epitaxy (MEE) for the GaPN layers were demonstrated to improve the luminescence efficiency. 100-nm-thick GaPN layers were grown on GaP (001) substrates by low-temperature MEE (LT-MEE) at 500 °C with high temperature MEE (HT-MEE) at 580 °C with an rf-MBE apparatus. The change of the surface reconstruction was clearly seen in InGaN layers. In addition, we observe a very pronounced shift of the PL peak energy. Strikingly, higher misorientation (i.e., lower In incorporation) gives a blue shift in the PL peak energy. Strikingly, higher misorientation (i.e., lower In content) leads to higher alloy disorder related to In segregation processes, clearly seen in InGaN layers. In addition, we observe a very pronounced influence of GaN substrate misorientation on the hole concentration in GaN.

Mg layers. A discussion of the microscopic origin of the observed phenomena based on substrate-morphology related effects will be given.

Influence of the Illumination on the Spin Splitting of the Two-Dimensional Electron Gas in AlxGa1-xN/GaN Heterostructures: Ning Tang; Bo Shen; Kui Han; Zhijiao Yang; Zhi xin Qin; Guoyi Zhang; Tie Lin; Wenzheng Zhou; Junhao Chu; State Key Laboratory of Artificial Microstructure and Mesoscopic Physics, School of Physics, Peking University; National Laboratory for Infrared Physics, Shanghai Institute of Technical Physics, Chinese Academy of Sciences

Spin splitting of the two-dimensional electron gas (2DEG) in AlxGa1-xN/GaN heterostructures has been investigated by means of magnetotransport measurements under the illumination at low temperatures. The beating patterns in the oscillatory magnetoresistance originating from zero-field splitting and magnetointersubband scattering (MIS) effects of the 2DEG are observed in this study. Corresponding to the shift of the beating nodes originating from zero-field spin splitting, it is found that the spin splitting energy decreases after the illumination. It is also found that the illumination decreases the electric field at AlxGa1-xN/GaN heterointerfaces. Based on the experimental results, it is suggested that the zero-field spin splitting of the 2DEG in AlxGa1-xN/GaN heterostructures mainly arises from the Rashba effect.

Infrared Microphotoreflectance Spectra of InN: Kazutoshi Fukuji; Kenta Kurihara; Tooru Yanagawa; Akio Yamamoto; University of Fukui

Investigations into electrical properties of InN thin films by electric measurement methods often have some discrepancies which are probably due to the existence of oxides, interface and/or surface charge accumulations, etc. The optical measurement methods, for example infrared reflectance measurements, also give some information related to charge concentrations, mobility, etc. In previous work, we derived not only TO and LO phonon frequencies, but also plasma frequencies and their damping factors from fitting infrared reflectance spectra at the theoretical formula, and we discussed the carrier concentration of InN thin films. In this work, we have carried out infrared microphotoreflectance measurements to extend this method to the local electric information of thin films.

Interplay between Strain and Composition in AlInN Alloys: Effect on the Validity of Vegard’s Law: V. Darakchieva; M. Beckers; L. Hultman; B. Monemar; J.-F. Carlin; N. Grandjean; Linkoping University; Ecole Polytechnique Federale de Lausanne

AlInN alloys have lately attracted a lot of attention due to the large energy range covered by their band gap and the possibility for lattice matching to GaN. The physical properties of ternary compounds are typically discussed based on Vegard’s law. However, recent theoretical and experimental works on AlInN alloys revealed some deviations from Vegard’s law for this material system. Correction factors that largely differ depending on the growth peculiarities, material properties, composition range and particular method used to extract alloy composition have been suggested and motivated the need of further investigations. In this work we present comparative study on the composition of AlInN alloys by X-ray reciprocal space mapping (RSM) and Rutherford back-scattering. The effects of strain relaxation and type of strain in the films on the extracted composition from the RSM are discussed and the implications on the validity of Vegard’s law are outlined.

Local Vibration Modes and Nitrogen Incorporation in AlGAs: N Layers: S. Lazic; Eva Gallardo; J. Calleja; J. Miguel-Sanchez; M. Montes; A. Hierro; R. Gargallo-Caballero; A. Guzman; E. Muñoz; A. M. Teweldeberhan; S. Fahy; Dep. of Physics of Materials, Universidad Autonoma de Madrid; Dep. of Physics of Materials, Universidad Autonoma de Madrid; Instituto de Sistemas Optoelectronicos y Microtecnologia, Universidad Politecnica de Madrid; Tyndall National Institute

Raman scattering measurements in dilute AlGAs:N films grown by plasma-assisted molecular beam epitaxy on (100) GaAs substrates reveal strong local vibration modes (LVM) associated to N complexes. The LVM observed frequencies around 325, 385, 400, 450 and 500 cm-1 are in fair agreement with density functional theory supercell calculations of AlGaN_N.
Technical Program

Low-Temperature Grown Composititionally Graded InGaN Films: N. Miller1; R. E. Jones2; K. M. Yu3; P. Flannigan4; J. Wu5; J. W. Ager6; Z. Lillentelt-Weber7; E. E. Haller8; W. Walukiewicz9; T. L. Williamson10; M. A. Hoffbauer11; J. A. Lockwood12; T. L. F. Pfitzner13; R. W. Whatmore13; 1Department of Materials Science and Engineering, University of California, Berkeley; 2Materials Sciences Division, Lawrence Berkeley National Laboratory; 3Materials Sciences Division, Lawrence Berkeley National Laboratory; 4Department of Materials Science and Engineering, University of California, Berkeley; 5Chemistry Division, Los Alamos National Laboratory

Energetic neutral atomic-beam lithography/epitaxy (ENABLE) provides a larger N atom flux and eliminates the need for high substrate temperatures as compared to molecular beam epitaxy making isothermal growth over the entire InGaN alloy composition range possible without phase separation. 500-800 nm thick composititionally graded InGaN films were grown by ENABLE at -450 °C: (1) with the Ga-rich material on the surface and (2) with the In-rich material on the surface. Rutherford backscattering spectrometry (RBS), transmission electron microscopy, x-ray diffraction, absorption spectroscopy, photoluminescence, and Hall effect measurements were used to assess the thickness, composition, crystalline quality, and optical and electrical properties of the films. The RBS and Hall effect data were used to model the electrical properties and expected distribution of free electrons throughout the thickness of the films. The results establish the new ENABLE method as uniquely capable of growing composititionally graded InGaN films and possibly InGaN/GaN heterostructures.

Luminescence and Vibrational Properties of Erbium-Implanted Nanoporous GaN: Chew Beng Soh1; Sio Jin Chua1; Si Hui Sim2; Sudhiranjan Tripathy3; E. Alves4; 1Institute of Materials Research and Engineering; 2National University of Singapore; 3Instituto Tecnológico e Nuclear

Implantation of Erbium (Er) into GaN is useful in creating selected areas to emit at the green, yellow and infrared wavelengths. Enhanced Erbium activation is obtained when Erbium is implanted into porous GaN formed by electrochemical etching than into as-grown GaN. This is due to the increase in surface area for light extraction and the availability of more free surfaces to accommodate strain when it is annealed. Furnace annealing at 1100 deg for 30 mins in nitrogen gives rise to higher band-edge photoluminescence intensity. Apart from the host GaN photon modes, we have also observed disorder-induced lattice vibrations at 170, 200 and 350-365 cm-1 from Er-implanted porous GaN. The E2 (high) mode of GaN also shifts towards higher energy at higher annealing temperatures, indicative of more Erbium occupying the VGa site (ionic radii of Er > Ga) and hence increasing the compressive stress in the GaN crystal lattice.

Luminescence Property of GaPN Layer Grown by OMVPE: Susumu Hatakakeka1; Akihiro Wakahara2; Yoshiyuki Nakashishi2; Yuzo Furukawa2; Hiroshi Okada1; Hiro Yoneyui1; Toyoohashi University of Technology

GaPN is expected to realize Si-based monolithic optoelectronic integrated circuits owing to lattice-match to Si. (In)GaPN based light emitting diodes on Si have been realized by molecular beam epitaxy (MBE). However, GaPN grown by MBE showed thermal quenching in photoluminescence (PL) intensity owing to point defects were induced by N-radical. In this work, we try to improve luminescence property of GaPN using organometallic vapor phase epitaxy (OMVPE) which is radical-free growth method. GaPN layers were grown on GaP(100) using trimethylgallium (TMGa) or triethylgallium (TEGa). Unintentional carbon incorporation in GaPN by TEG decreased by 1/4 compared with TMGa. As a result, non-radiative recombination centers decreased by about two orders of magnitude by TEGa. Compared to MBE, Full width at half maximum (FWHM) of PL peak in OMVPE-GaPN was 140meV whereas FWHM of MBE-GaPN was 200meV. PL intensity of deep level has decreased by about two orders of magnitude using OMVPE.

MBE Growth and Characterization of Mg-Doped InGaN and InAlN: Kristerh Mathews1; Xiaodong Chen2; Dong Hao3; William Schaff3; Lester Eastman3; 1Cornell University

We report on the growth of Mg-doped InGaN and InAlN by molecular beam epitaxy. We successfully obtain high quality InxGa1-xN films on (0001) sapphire substrate. Phase separation does not occur in InxGa1-xN films with Indium content up to 0.88. Hall measurement shows that hole concentration of 7.7×1017 cm-3 is achieved on Mg-doped In0.04Ga0.96N. When x>0.11, the Hall samples exhibit strong n-type polarity, whereas p-type polarity is confirmed by hot probe measurement for all of Mg-doped InGaN. Ni/Au film is deposited on Mg-doped InGa1-xN as the contact metal. The contact resistance as high as 2700 Ωmm is obtained when x=0.25 while it is only 0.03 Ωmm when x=0.85. High quality crack-free InAlN film is also grown on sapphire substrate with AlN/InN quantum-well buffer layer. So far all of Mg-doped InAlN films show n-type polarity by Hall measurement, but it is promising to achieve p-polarity with varying Mg flux.

Mg-Doped InN Epilayers and in Rich InGaN Alloys: Neelam Khan1; Neeraj Nepal1; Ashok Sedhain1; Hongxing Jiang1; Jingyu Lin1; 1Kansas State University

Mg-doped InN epilayers and In-rich InGaN alloys were grown on sapphire substrates by metal organic chemical vapor deposition. Effects of Mg concentration on the structural, electrical and photoluminescence (PL) emission properties of Mg-doped InN have been investigated. PL studies revealed a dominant emission line at ~0.76 eV in Mg-doped InN epilayers, which was absent in undoped InN epilayers and was about 60 meV below the band edge emission peak at ~0.82 eV. The PL peak position and the temperature dependent emission intensity corroborated each other and suggested that the Mg acceptor level is dominant in InN is about 60 meV above the valence band maximum. Mg doped InGaN epilayers have also been grown and their structural, optical, and electrical properties have been measured and will be reported. The implications of our results on achieving p-type InGaN alloys with high In-contents will be discussed.

MOVPE Growth and Photoluminescence Properties of InAsN QDs: Shigenobu Kuboya1; Thieu Quang Tu1; Shun Takahashi2; Fumihiro Nakajima1; Ryuuji Katayama1; Kentaro Onabe1; 1University of Tokyo

The self-assembled InAsN quantum dots (QDs) were grown on GaAs (001) by MOVPE. With the DMHy (N precursor) supply, the dot width decreased from 31 nm to 18 nm and the dot density increased from 3.3×1010 cm-2 to 4.1×1010 cm-2 at the equivalent nominal thickness of 2.6 ML. The reduction of the dot size is attributed to the increased wetting layer thickness for the QD formation. The increase of the dot density is attributed to the decreased migration lengths of the surface species. The RT-PL peak wavelengths of the 2.6 ML InAs and InAsN QDs were 1135 nm and 1159 nm, respectively. This red-shift is caused by the N-incorporation-induced bandgap reduction, which is dominant over the possible blue-shift for the reduced dot sizes (quantum size effect). The temperature dependence of PL shows that the N-related carrier localization is no significance in the QDs in contrast with the bulk InAsN films.

Optical Gain of Eu+ Ion Implanted AlGaN and Its Al Compositional Dependence: Akihiro Wakahara1; Takashi Shimojo1; Hiroaki Kawai1; Hiroshi Okada1; Takeshi Ohshima2; Shin-ichiro Sato2; 1University of Tokyo

Optical properties, such as optical modal gain and optical loss, of Eu implanted AlGaN with various AlN molar fractions were measured to investigate the potential application of Eu-implanted AlGaN for optical devices. The optical gain measured at 300K by using variable length stripe (VSL) method for Eu-implanted GaN is as high as 50cm-1, which is the same order of magnitude of the AlN grown AlGaN. The optical gain increases with increasing the AlN molar fraction and shows maximum value of ~130cm-1 around the AlN molar fraction of 0.2. While the optical loss is of the order of ~10cm-1.
Optical Properties of Cubic InN from Mid-IR into the VUV Range: Pascal Schlöfl; Christian Napieral; Rüdiger Goldhahn; Gerhard Gobsch; Jörg Schörrmann; Donat As; Klaus Lischka; Martin Feneberg; Klaus Thonke; Frank Fuchs; Friedhelm Bechtold; TU Ilmenau; University of Paderborn; Friedrich-Schiller University Jena

We present a comprehensive optical characterization of single crystalline cubic (c) InN films grown by MBE on c-GaN/3C-SiC pseudo-substrates. Ellipsometry was applied in order to determine the dielectric function (DF) from the mid-infrared into the VUV spectral region. All layers show strong emission around 0.5 eV at low temperature. The high electron densities cause pronounced Stokes and Burstein-Moss shifts at the gap. Taking into account carrier-induced band-gap renormalization, the non-parabolicity and the filling of the conduction band we determine a zero-density c-InN band gap of 0.61 eV which is about 70 meV lower than for hexagonal InN. In addition, the DF shows pronounced features at high photon energies. The transition energies of the band-to-band transitions are in excellent agreement with the results of DFT-LDA calculations for the electron-hole interaction was taken into account.

Photoluminescence of Cubic InN Films on MgO(001) Substrates: Takeru Inoue; Youhei Iwashashi; Shingo Oishi; Misao Orihara; Yasuto Hizikata; Hiroyuki Yaguchi; Sadafumi Yoshida; Saitama University

Although there have recently been a lot of reports on the growth and characterization of hexagonal InN (h-InN), the growth of cubic InN (c-InN) films has been less reported. Furthermore, the physical properties of c-InN, such as band gap energy, have been still unclear. In this study, we report on the photoluminescence (PL) from c-InN films grown on MgO substrates with a cubic GaN underlayer by RF-N2 plasma molecular beam epitaxy. A single PL peak was observed at 0.47 eV. By analyzing the reflectance spectra of c-InN films, we found c-InN is a direct transition type semiconductor and that the band gap energy is 0.48 eV. The difference in the PL peak energy between h- and c-InN is in good agreement with the difference predicted by ab initio calculations.

Photoluminescence Study of Hexagonal InN/InGaN Quantum Well Structures Grown on 3C-SiC (001) Substrates by Molecular Beam Epitaxy: Shigeru Hirano; Takeru Inoue; Go Shikata; Misao Orihara; Yasuto Hizikata; Hiroyuki Yaguchi; Sadafumi Yoshida; Saitama University

We have studied the well-width dependence of photoluminescence from hexagonal InN/InGaN multiple quantum well structures grown on 3C-SiC (001) substrates with an InGaN underlayer by plasma assisted molecular beam epitaxy. A single PL peak was observed at 0.47 eV. By analyzing the reflectance spectra of c-InN films, we found c-InN is a direct transition type semiconductor and that the band gap energy is 0.48 eV. The difference in the PL peak energy between h- and c-InN is in good agreement with the difference predicted by ab initio calculations.

Raman Study of High-N-Content GaN Films Grown by MOVPE: Fumihiro Nakajima; Sakumon Sanporini; Wataru Ono; Shigeuki Kaboyan; Ryuji Katayaman; Kentarô Onahamen; University of Tokyo; Chulalongkorn University

MOVPE-grown GaAsN films with the N content up to 5.1% were studied by micro-Raman scattering spectroscopy. In the Raman spectra, besides GaAs LO(T), additional peaks including one caused by the Ga-N localized vibrational mode (LVM), have developed with increasing N content. Additional peaks except LVM are caused by the inherently forbidden modes which have appeared due to the lattice-orientation disorder caused by N incorporation. LVM is considered to cause the weaker temperature dependence of the bandgap in higher N-content films previously discussed. The N contents estimated from the relative intensities of LVM and LO(T) were identical with those determined from X-ray diffraction for lower N contents. The discrepancy for higher N contents (N>3%) suggests the significance of the point defects like N interstitials and vacancies. An improved coincidence was achieved after annealing the films, indicating that more N atoms occupy the proper lattice sites with less point defects.

Structural and Optical Properties of In-Rich InGaN Dots Grown by Metalorganic Chemical Vapor Deposition: Wen-Chieh Bai; Hujuan Lin; Wen-Chen Ke; Wen-Hao Chang; Wu-Ching Chou; Wei-Kuo Chen; Ming-Chih Lee; National Chiao Tung University

Surface morphologies, alloy compositions and emission properties of In-rich InGa1-xN dots (x ~ 0.87) grown by metalorganic chemical vapor deposition at various growth temperatures (550-750°C) were investigated. The nucleation of InGaN dots was found to be governed by the surface migration of In adatoms. With the increasing growth temperature, the incorporation of Ga into InN during the growth of InGaN dots is kinetically inhibited, which tends to decompose into In-rich islands and a thin Ga-rich layer. These In-rich islands exhibit PL emission in the near-infrared range. Another visible emission band was also observed for samples grown at higher temperatures. The formation of a thin Ga-rich layer is likely to be responsible for the visible emission.

Synthesis of Rare-Earth Activated AlN and GaN Powders via a Three-Step Conversion Process: Jonathan Tao; Nestor Perea-Lopez; Joanna Mekitrkic; Jan Talbot; Madis Raukas; Joe Laski; KaiLash Mishra; Gustavo Hirata; University of California, San Diego; Osram Sylvania; CCMC-UNAM

Using a three-step solution method, we have successfully synthesized rare-earth activated AlN, GaN, as well as undoped GaAIN. Rare-earth activators including Eu2+, Tb3+, and Tm3+ are first added as nitrate precursors to an aqueous Al(NO3)3 precursor. Then the mixture is converted into Al(OH)3 at room temperature. The product is then mixed with aqueous NH4F to form rare-earth activated (NH4)3AlF6. The conversion process is complete when the hexafluoride compound is flushed with anhydrous ammonia to produce the final nitride product. GaN and GaAIN are synthesized similarly. Single phase AlN, GaN and GaAIN formation has been confirmed by XRD. EDS measurements indicates an oxygen concentration of approximately 4 at% in GaN powders, and slightly higher in AlN powders. Luminescence measurements show clearly observable emission from Eu2+ and Tb3+ co-activated AlN samples as well as emission from Dy3+ and Tm3+ co-activated AlN samples.

Temperature Dependence of the Density of the Two-Dimensional Electron Gases in AlxGa1-xN/GaN Heterostructures: Maqiu Wang; Bo Shen; Ning Tang; Fujun Xu; Sen Huang; Jian Xu; Zhenlin Miao; Zhijian Yang; Zhixin Qin; Guoyi Zhang; State Key Laboratory of Artificial Microstructure and Mesoscopic Physics, School of Physics, Peking University

Temperature dependence of the density of the two-dimensional electron gas (2DEG) in Al0.18Ga0.82N/GaN heterostructures has been investigated by means of high temperature Hall measurements from room temperature to 500°C before and after SiNx passivation. In as-grown heterostructures, the 2DEG density decreases with increasing temperature from room temperature to 250°C, and then changes to increase with increasing temperature at higher temperatures, which is suggested to be caused by the change of the conduction band offset and the increased background electron concentration in GaN layer at higher temperatures, respectively. Theoretical calculation of the 2DEG density in AlxGa1-xN/GaN heterostructures at various temperatures is consistent with the experimental results. The 2DEG density increases much after SiNx passivation and it is revealed that the increased 2DEG density is mainly caused by the excess Si dangling bonds at the SiNx/Al0.18Ga0.82N interface and Si atoms incorporated into the Al0.18Ga0.82N barrier during the SiNx growth.

The Comparison of Structural, Optical, and Magnetic Properties of Undoped and P-Type GaN Implanted with Mn+ (1, 5 and 10 at%): Yoon Shori; H. Jeon; C. Park; S.-W. Lee; T. Kang; Eun Kim; D. Fu; J. Lee; Dongduk University; Hanyang University; Wuhan University; Gyeongsang National University

Undoped GaN epilayers were prepared by molecular beam epitaxy(MBE) and subsequently implanted with the Mn+ of 1 and 10 at%. P-type GaN epilayers were grown by metalorganic chemical vapor deposition (MOCVD) and subsequently implanted with the Mn+ of 5 and 10 at%. In relation to Mn-activation, it was confirmed that the photoluminescence peak at 2.5 eV
in a donor-Mn acceptor transition (D-A pair) and the photoluminescence peak around 3.0 eV is a conduction band to Mn acceptor transition. The undoped and p-type GaMnN epi-layers measured at 10 K with the Mn concentration of 10% showed clear ferromagnetic hysteresis loop with increasing annealing temperature and ferromagnetic behavior persisting up to 300 K. However, the magnetic properties of the p-type GaMnN were enhanced in comparison with those of the undoped GaMnN. And also, the p-type GaMnN epilayer with the Mn concentration of 5% showed weak and unstable ferromagnetic hysteresis loop.

**Thermal Stability, Morphological and Structural Properties of Metalorganic Vapor Phase Epitaxy Grown AlInN on Si(111):** Aniko Gudelcze\(^\d\); Jürgen Bläsi\(^\d\); Armin Dadgar\(^\d\); Christoph Humm\(^\d\); Thomas Hempel\(^\d\); Jürgen Christen\(^\d\); Alois Krost\(^\d\); Otto-von-Guericke Universität Magdeburg, FND/IEP/AHE; Otto-von-Guericke-Universität Magdeburg, FND/IEP/AFP

AlInN is an interesting compound for electronic and optoelectronic applications as high-current FETs and for unstrained Bragg mirrors lattice matched to GaN. We investigated AlInN layers on GaN/Si(111) with In concentrations between 9%<x<16% and a maximal thickness of 100 nm grown by MOVPE. Subject to the In concentration the layers are fully pseudomorphic or exhibit both relaxed and pseudomorphic parts. The thermal stability of the layers with x<22% was investigated between 30 and 960°C. It is considerably depending on the degree of relaxation: after different thermal treatment, the relaxed areas show decreasing quality, a well-pronounced phase separation and a loss of Indium. An additional effect under thermal treatment is an observably higher extension of relaxed regions with increasing lattice mismatch. By high-resolution X-ray diffraction and field emission scanning electron microscopy (FESEM) morphological characteristics in the alloy, as the values of twist and lattice constants, In-sublimation and relaxation were determined.

**Ultra-High Temperature Microwave Annealing of In-Situ Doped and Ion-Implanted GaN Layers Using Protective Ceramic Caps:** Suddath Sundaresan\(^\d\); Madhu Murthy\(^\d\); Nadeemulah Malikah\(^\d\); Albert Davydov\(^\d\); Elba Gomar-Nadal\(^\d\); R. Vispute\(^\d\); M. Mastro\(^\d\); Charles Eddy\(^\d\); R. Holm\(^\d\); R. Henry\(^\d\); Syed Qadri\(^\d\); Yong-lai Tian\(^\d\); Mulupri Rao\(^\d\); George Mason University; National Institute of Standards and Technology; University of Maryland; Naval Research Laboratory; LT Technologies

Using a novel microwave RFA system capable of ultra-fast heating rates > 400°C/s, we were able to anneal Mg in-situ doped GaN at 1300–1500°C, when the GaN is protected by PLD AlN cap. The surface of the AlN capped GaN layer annealed at 1500°C for 5 s is very smooth (RMS roughness = 0.6 nm). An electron-beam deposited MgO cap successfully protected the GaN surface during microwave annealing only up to 1300°C, but significant GaN decomposition is observed for higher temperature anneals. PL and Hall measurements performed on the AlN capped samples indicate that the 1500°C / 5 s microwave annealing is more effective than 1300°C/5 s microwave annealing in activating the Mg-dopants by decreasing the concentration of compensating donor levels. Detailed results on XRD, PL, and electrical characterization of in-situ and ion-implantation Mg-doped GaN will be presented.

**Structural and Optical Characterization of InN/InGaN Multiple Quantum Wells Grown by Plasma-Assisted MBE:** Javier Grande\(^\d\); Ana Bengoechea\(^\d\); Miguel Sánchez-Garcia\(^\d\); Enrique Callaja\(^\d\); Esperanza Luna\(^\d\); Achim Trampert\(^\d\); Snezana Lazic\(^\d\); Eva Gallardo\(^\d\); José Calleja\(^\d\); Instituto de Sistemas Optoelectrónicos y Microtecnología-Escuela Técnica Superior de Ingenieros de Telecomunicación-Universidad Politécnica de Madrid; Paul Drude Institute; Universidad Autonoma de Madrid

This work reports on the growth by PA-MBE and characterization of InN/InGaN MQW samples. Samples were characterized by SEM, TEM, AFM, XRD, PL and Raman spectroscopy. Low temperature PL spectra of a 10 x InN/In\textsubscript{0.85}Ga\textsubscript{0.15}N MQW sample reveal an emission at 0.81 eV (1.53 μm) from the MQW together with an emission from the barriers modulated by Fabry-Perot oscillations. Satellite peaks up to the second order are observed at the XRD scans. XRD simulation estimates a well and barrier thicknesses of 2.4 nm and 9.1 nm, respectively. The crystal quality of the interfaces is analyzed by TEM. Raman spectroscopy will give information on the strain present in the overall structure. The growth of intermediate blocking layers to avoid the dissociation of the InN wells will be also carried out in order to perform a high temperature p-type doped GaN cap layer on top of the MQW.

**Carrier Dynamics in Wide-Band-Gap AlGaN/AlGaN Quantum Wells:** Gintautas Tamulaitis\(^\d\); Rusla Elba Gomar-Nadal\(^\d\); Miguel Sánchez-García\(^\d\); Enrique Calleja\(^\d\); Esperanza Luna\(^\d\); Achim Trampert\(^\d\); Snezana Lazic\(^\d\); Eva Gallardo\(^\d\); José Calleja\(^\d\); Instituto de Sistemas Optoelectrónicos y Microtecnología-Escuela Técnica Superior de Ingenieros de Telecomunicación-Universidad Politécnica de Madrid; Paul Drude Institute; Universidad Autonoma de Madrid

We report on time-resolved photoluminescence (PL) spectroscopy and light-induced transient grating technique studies of carrier dynamics in wide-band-gap AlGaN multiple quantum wells (MQWs). A set of Al\textsubscript{0.35}Ga\textsubscript{0.65}N/Al\textsubscript{0.49}Ga\textsubscript{0.51}N MQWs with fixed barrier width and well widths varying from 1.65 nm to 5.0 nm has been grown by metal-organic chemical vapor deposition. The radiative decay time, which affects the initial part of PL intensity decay after pulsed excitation, is influenced by screening of the built-in electric field, which spatially separates the electrons and holes. This fast PL decrease is more pronounced in wider quantum wells and at higher initial carrier density but saturates when the carrier density is high enough to completely screen the built-in electric field. The lifetime of nonequilibrium carriers (excitons), which is determined by nonradiative recombination, increases with decreasing the well width. The effect was interpreted by stronger localization preventing carrier migration to nonradiative recombination centers.

**Biexciton Binding Energy of GaN Films Grown on Various Substrates:** Saburo Adachi\(^\d\); Yasumori Toda\(^\d\); Hokkaido University

The optical investigation for a series of excitors as neutral (or charge) excitons and multie excitons has been a focus of constant attention in semiconductors with various materials and structures. In particular, biexciton has been investigated systematically in the confined structures and Haynes rule is verified experimentally and theoretically. While the strain modifies the band structure and affects the binding energy, the influence has not been investigated so far in GaN. We report here the biexciton binding energy of GaN under biaxial and uniaxial strains investigated by spectrally-resolved four-wave mixing (FWM) technique, where wurtzite GaN with different thickness grown on various substrates such as sapphire, a-sapphire, and 6H-SiC were used.

**Materials Issues**

**Ozone and UV Assisted Oxidation of InN Surfaces:** Gernot Ecke\(^\d\); Chunyu Wang\(^\d\); Volker Cimalla\(^\d\); Vadim Lebedev\(^\d\); Oliver Ambacher\(^\d\); TU Ilmenau

High-quality InN layers suffer from extremely high electron concentrations especially at surfaces and interfaces. Even if their electron mobility could be extremely high, this prevents the electron depletion and so the application of this outstanding material in field effect transistors. Surface treatments like oxidation assisted by UV irradiation under Ozone atmosphere results in a decrease of the surface electron concentration. This has been confirmed by resistance and Hall measurements. In order to investigate this mechanism and understand the band bending, laterally highly resolved Auger measurements have been carried out. As the result a correlation of the surface O content and the Auger peak shift to lower energies was found. The measurements show that the oxidation is laterally inhomogeneous and depends on the quality of the InN layer. This oxidation procedure helps to enable InN for FET device application.
Cathodoluminescence Nano-Characterization of a-Plane GaN ELOG Structures: Direct Imaging of Growth Domains, Morphological Defects, and Impurity Incorporation

Barbara Bastek; Frank Bertram; Juergen Christen; Tim Werner; Markus Weyers; Michael Kneissl;
Otto-von-Guericke-University Magdeburg; Ferdinand-Braun-Institut für Höchstfrequenztechnik, Berlin; Ferdinand-Braun-Institut für Höchstfrequenztechnik, Berlin and Institute for Solid State Physics, Technical University Berlin

The distinctly different ELO growth regimes of a-plane GaN ELOG resulting from stripe mask orientation in [0001], [01-11], and [01-10], respectively, were directly imaged by highly spatially and spectrally resolved cathodoluminescence microscopy (CL). The characteristic basal plane stacking fault (BSF) emission at 3.41eV dominates the spatially integrated luminescence. In contrast, local spot mode CL evidences a completely different picture: striation like patterns of different CL wavelength strictly oriented in individual crystal directions and originating from either BSF, prismatic stacking fault (PSF), and/or impurity related DAP emission are clearly resolved. Preferential local impurity incorporation is evidenced. While [0001]-stripes result in symmetrical ELOG, for [01-10]-stripes almost no overgrowth in [0001]-1 but a strong lateral overgrowth in [0001] is found. Perfect, homogeneous and unstrained a-oriented, laterally c-direction grown GaN domains form, dominated by intense, sharp (0001) emission at 3.471eV (relaxed GaN). No BSF, PSF or other defect CL is found there!

Comparative Raman Study of the Anharmonic Properties of GaN and ZnO: Jose Menendez; Lingyun Shi; Christian Poweleit; Arizona State University

We report a comparative study of the temperature dependence of the frequency and linewidth of the Raman-active E modes in GaN and ZnO. The spectra were obtained with an ultra-high resolution Raman instrument capable of measuring linewidths as small as 0.05 cm⁻¹. The high resolution of the spectra makes it possible to detect asymmetries not only in the ZnO spectra, as previously reported, but also in GaN. Another intriguing finding is that the temperature dependence of the high-energy E phonon frequency in ZnO is not monotonic: the mode frequency increases as a function of temperature at low temperatures, and it starts to decrease around 150 K. We use the similarity of the phonon dispersion curves in both materials to introduce a simple but realistic model of the Raman lineshape and frequency that explains the above findings and provides a unified description of the anharmonic properties of GaN and ZnO.

Effects of Grown-In Defects on Electron Spin Dynamics in Dilute Nitride Alloys: X. Wang; Irina Boyanová; Weinmin Chen; Y. Hong; Charles Tu; Linkoping University, University of California

Adding to unusual electronic properties of novel dilute nitrides is strong electron spin polarization observed upon optical orientation in Ga(In)NAs, attributed to strong spin dependent recombination (SDR) facilitated by N incorporation. However, the origin of defects involved in SDR and whether it is inherent to all dilute nitrides remain unknown. This work tackles these important issues by correlating electron spin dynamics with defect properties of several dilute nitride materials, such as Ga(In)N and Ga(In)NAs alloys. Optical orientation measurements are used to evaluate presence of the SDR processes and to determine its efficiency, whereas the optically detected magnetic resonance technique is employed for chemical identification of responsible defects. Effects of defect types (e.g. As antisites vs Ga interstitials) and their concentrations are closely examined by varying conditions of the growth. We have previously demonstrated that spectrally-resolved four-wave mixing (SR-FWM) highlights the anisotropically polarized excitons in the uniaxially strained GaN films. In this work, we have applied this technique to the GaN films on isotropic substrates, and have examined the sensitivity of the technique. The measurements have been performed with the collinearly polarized two-pulse FWM in reflection geometry, in which the enhancement of sensitivity for exciton polarizations is achieved by nonlinear response of the oscillator strength. Several samples show the anti-correlated polarizations in each exciton, suggesting the existence of weak uniaxial strain. The minimum changes of the polarized FWM intensity and exchange energy splittings are found in the 2.3 μm-thick GaN on 6H-SiC, and give a resolution of uniaxial strain of 5.0×10⁻⁶, which is comparable with the resolution of conventional X-ray diffraction analysis.

Internal Quantum Efficiency of AlxGa1-xN (0<x<1) on AlN Template: Naritito Okada; Motoaki Iwaya; Satoshi Kamiyama; Hiroshi Amano; Isamu Akasaki; Hissaaki Maruyama; Takashi Takagi; Akira Bando; Hideaki Murotani; Yoichi Yamada; Meijo-University; Ibiden Company, Ltd; Showa Denko K.K.; Yamaguchi University

High-performance UV light emitting devices are applicable in many fields including biomedical applications. To realize such novel applications, it is essential to grow high crystalline quality AlGaN without cracks. When AlGaN is grown on AlN, crack can be suppressed. In addition, AlN can be used as a window for the UV light because of its wide bandgap. Therefore, AlN template is ideal for the growth of AlGaN. However, internal quantum efficiency (IQE) of AlGaN on AlN template has not been reported so far. In this study, we performed MOVPE growth of thick AlGaN with the whole compositional range on AlN templates. Then, the IQEs were evaluated by comparing photoluminescence peak intensity at 7K and room temperature.

Intrinsic Electric Fields in Wide Band Gap AlGaN Quantum Wells: Saulius Marcinkevicius; Andrea Pinos; Kai Liu; Dmitriy Veksler; Michael Shur; Jianping Zhang; Remis Gaska; Royal Institute of Technology; Rensselaer Polytechnic Institute; Sensor Electronic Technology, Inc.

Built-in electric fields are studied in in AlxGaN-AlxN-AlxGa1-xN quantum wells (QWs) with different Al molar fractions and QW and barrier widths. The field magnitude is evaluated by comparing bias- and free carrier density-induced Stark shifts for QWs embedded into p-i-n structures. For lower Al composition, wells were studied by analyzing temperature-dependent and time-resolved photoluminescence spectra. We observed carrier transfer between weakly and strongly localized states which resulted in a stronger blue emission with increasing temperature and we analyzed its effects on the spectra in terms of the quantum confined screening effect. Time-resolved measurements yielded lifetimes of various transitions which indicated different origins ranging between ~120 ns and ~1300 ns.

Excitonic Spin Relaxation Dynamics in GaN: Christelle Brimont; Mathieu Gallart; Olivier Créguet; Bernd Hönerlage; Pierre Gillot; Institute of Physics and Chemistry of Materials of Strasbourg-Group of Non-Linear Optics and Optoelectronics; University of Louis Pasteur-National Center of Scientific Research

Performing a non-degenerate pump-probe experiments, we study the relaxation dynamics of spin-polarized excitons in wurtzite epitaxial GaN. For negative time delays between pump and probe pulses, the time- and spectrally-resolved differential reflectivity (DR/R) displays a T2 rise time with spectral oscillatory features in the vicinity of the excitonic resonances: These oscillations are caused by interference between the pump electric field and the probe induced polarization within the sample. For positive time delays, the analysis of DR/R of the two circular probe components allows us to extract, for each spin relaxation process, the characteristic time constants. The spin relaxation of the exciton as a whole is negligible in regard to the spin relaxation of the individual carriers. We determined Te=15 ps for the electron in the conduction band, Th=5 ps, and Thh=1.5 ps for the heavy hole and for the light hole, respectively.

Highly Sensitive Optical Probe for Uniaxial Strain in GaN Epitaxial Films: Yasunori Toda; Satoru Adachi; Tetsuro Ishiguro; Kazuyuki Tadatomo; Katsuyuki Hoshino; Hokkaido University; Yamaguchi University

We have previously demonstrated that spectrally-resolved four-wave mixing (SR-FWM) highlights the anisotropically polarized excitons in the uniaxially strained GaN films. In this work, we have applied this technique to the GaN films on isotropic substrates, and have examined the sensitivity of the technique. The measurements have been performed with the collinearly polarized two-pulse FWM in reflection geometry, in which the enhancement of sensitivity for exciton polarizations is achieved by nonlinear response of the oscillator strength. Several samples show the anti-correlated polarizations in each exciton, suggesting the existence of weak uniaxial strain. The minimum changes of the polarized FWM intensity and exchange energy splittings are found in the 2.3 μm-thick GaN on 6H-SiC, and give a resolution of uniaxial strain of 5.0×10⁻⁶, which is comparable with the resolution of conventional X-ray diffraction analysis.

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content, the field is about 1 MV/cm, for Al0.35Ga0.65/Al0.5Ga0.5N QWs, the field is considerably smaller, ~0.3 MV/cm. Strong sublinear dependence of polarization on Al molar fraction is suggested as a possible reason for this observation. The Stark shift increases with increased QW and barrier width; the latter dependence agrees with the calculated distribution of the built-in field between the quantum well and barrier layers. After strong pulsed excitation, which leads to screening of the built-in fields, the field de-screening occurs with a characteristic time of 70 – 90 ps. The de-screening is faster in wider QWs because of a more efficient electron and hole separation.

**Luminescence Studies in Nitride Quaternary Alloys Double Quantum Wells:** S. C. P. Rodrigues¹; Luísa Scoldarò; M. N. d’ Eurydice¹; G. M. Sipahi¹; E. F. da Silva Jr.²; Universidade Federal Rural de Pernambuco, Departamento de Física; ¹University of Sao Paulo, Physics Institute; ²Universidade de São Paulo, Instituto de Física de São Carlos; ³Università Federal de Pernambuco, Departamento de Física

The quaternary AlGaN alloy can reach shorter wavelength as compared with a single quantum well, which is important in optical communication devices, operating at wavelengths of 1.3 and 1.55 µm, such as in optical fiber communication networks. In this work we study double quantum wells (DQWs) of nitride quaternary alloys in cubic phase. In this way it will be possible to obtain high optical gain without strain-induced piezoelectric and spontaneous polarizations effects. Quaternary derived p-doped systems are also investigated. Band structures and photoluminescence spectra calculations of Al_xIn_yGa_z-N/Al_xIn_yGa_z-N DQWs were performed by using the k.p theory and solving self-consistently the 8 x 8 Kane multiband effective mass/Poisson equations. We discuss the effects imposed by the Al and In molar fractions on the emission features of the systems. Our findings can be used as a guide for future experiments, helping on the design of optical communications devices.

**Micro-Raman Characterization of BGaN Growth on AIN Template Substrate:** Sidi Ould Saad Hamady¹; Tewfik Baghdadi¹; Simon Gautier¹; Jérôme Martin¹; Abdallah Ougazzaden¹; University Metz, Supelec; Georgia Institute of Technology

We have investigated the Raman spectra of BGaN layers grown by MOVPE on AIN template. The boron content covered the composition range from 0% (pure GaN) to 1.75%. The homogeneity of BGaN layers were studied by micro-Raman mapping and the phonon modes characteristics are determined as a function of boron content, according to the laser polarisation. These modes frequencies are shifted compared to that of pure GaN, and their intensities and linewidths depend on boron content. In particular the E2 and A1(LO) phonon modes shifts and linewidths strongly depend on boron composition. This behaviour is discussed according to the composition and strain effects and indicates a relaxation of the strain showing that the boron incorporation in GaN reduces the lattice mismatch with AIN substrate.

**MOVPE Growth and Investigation of AlInN/AIN Multiple Quantum Wells (MQW):** Christof Muander¹; Lars Rahimzadeh Khoshroo¹; Vladimir I. Kozlovskiy¹; Gennadi P. Yablonskii¹; Joachim Woitok²; Yilmaz Dikme³; I. Kozlovsky 2; Gennadi P. Yablonskii 3; Joachim Woitok 4; Yilmaz Dikme 5; ¹University of Fukui; 2Kanazawa University; 3Mie University; 4Chonbuk National University; 5Semiconductor Physics Research Center; 6Gwangu Institute of Science and Technology, Advanced Photonics Research Institute; 7LG Innotek

In this study, optical properties of InGaN-blue-LEDs fabricated on aligned micropits grown on wet-etched patterned sapphire substrates(WPSSs) were investigated with UV near-field scanning optical microscopy(NSOM). The GaN template grown on WPSS consisted of well aligned hexagonal depressions(micropits) with small horizontal regions inbetween them. The WPSSs led not only for the reduction of TDs but also for the enhancement of light extraction efficiency of fabricated LEDs. The horizontal MQW regions consisted of thicker wells and barriers compared to the inclined MQWs of the hexagonal depressions. The horizontal MQW regions show bright emission in NSOM image at a relatively longer wavelength than the inclined MQWs. It indicates that the fabricated LEDs posses low(horizontal) and high(inclined) luminescence energy regions acted as potential-well and -barrier along the lateral direction. By this potential variation across the lateral direction, the excited carriers are well confined in the horizontal MQWs observed as bright regions in the NSOM-mapping.

**Nonpolar GaN Layers Grown by Sidewall Epitaxial Lateral Overgrowth:** Optical Evidences for a Reduced Stacking Fault Density: Plamen Paskov¹; Bo Monemar¹; Motoaki Iwaya¹; Satoshi Kaniyama¹; Hiroshi Amano¹; Isamu Akasaki¹; ¹Linkoping University, Department of Physics, Chemistry and Biology; ²Meijo University, Faculty of Science and Technology

Nonpolar a-plane and m-plane GaN layers grown by MOCVD employing sidewall-seeded epitaxial lateral overgrowth (SELO) were studied by photoluminescence (PL), polarization dependent PL and micro-PL. The SELO technique makes use of grooved GaN templates with SO2 masks deposited on the terraces. The effects of both the groove orientations and the groove terrace width ratio on the emission spectra, particularly on the stacking fault (SF) related emission bands in the 3.29-3.42 eV region, were examined. The PL spectra of both types nonpolar layers reveal a significant reduction of the defect related emissions when the grooves are oriented perpendicular to the c-axis of GaN and the groove/terrace width ratio is smaller than one. The suppression of SF formation in the areas where a lateral overgrowth along the [0001] direction occurs is confirmed by spatially resolved micro-PL showing no SF related emissions over the terrace regions.

**Optical Transition Energy of Strained and Fully-Relaxed GaN Films:** Seogwoo Lee¹; ¹Tohoku University

Most of GaN-based devices have been heteroepitaxially grown. Hence lattice strain is induced in GaN epilayers. The bandgap energy of a semiconductor changes with temperature and strain. Although the temperature dependence of optical transition energy(OTE) of a semiconductor has been well expressed by Varshni’s equation, the effect of strain on this equation has not been evaluated. In order to evaluate the contribution of strain, we carried out detailed optical studies on a GaN layer grown on sapphire substrate with a CrN buffer layer. The GaN layer was partially detached from the sapphire substrate by selective chemical etching of the CrN buffer. Based on detailed micro photoluminescence and Raman scattering measurements on both etched and unetched parts of the GaN layer, we propose a new equation, which consists of temperature component and strain component. The impact of this new equation is that we can evaluate the OTE, once strain is evaluated.

**Photoluminescence Decay Processes in AlGaN Alloys:** Kazutoshi Fukuda¹; Naoto Nakagawa¹; Tomohide Sakai¹; Shun-ichi Naoe¹; Hideto Miyake¹; Kazumasa Hiramatsu¹; University of Fukui; ¹Kanazawa University; ²Mie University

Ternary AlGaN alloys are promising materials for ultraviolet (UV) optical devices. However, their low photoluminescence (PL) efficiency near band-edge excitonic PL at room temperature (RT) is one of the severe problems realizing UV emission devices. Then, it is important to study basic optical properties, such as PL decay processes. For InGaN PL decay processes, the time resolved decay (TRD) curves can be fitted as the extended exponential decay curves, which indicate that strong indium inhomogeneity plays
an important role. However, TRD curves of AlGaN can not be fitted as extended exponential functions, and we have been reporting that three single exponential functions model is appropriate for PL decay processes of AlGaN and InAlGaN. In this report, we present PL and PL excitation (PLE) spectra of each decay component, and their temperature dependence to investigate decay mechanisms of AlGaN alloys.

**Picosecond Exciton Spin Relaxation in Hexagonal GaN and Nanosecond Excitonic Spin Relaxation in Cubic GaN:** Atsushi Tackeuchi; Hirotaoka Otake; Taisuke Fujita; Takako Chimone; Ji-Hao Liang; Masatake Kajikawa; Fumiyoshi Takano; Hiro Akinaga; Waseda University; Stanley Electric Company Ltd; Nanotechnology Research Institute, AIST

The excitonic spin relaxations in hexagonal GaN and cubic GaN are observed by spin-dependent pump and probe reflectance measurements with subpicosecond time resolution. The A-band free exciton in hexagonal GaN shows a sub-picosecond spin relaxation of 0.47 ps at 150 K. The acceptor-bound exciton in cubic GaN shows the spin relaxation times of 1.40 – 1.14 ps at 15-50 K. Meanwhile the spin relaxation times in cubic GaN at 15 – 75 K are found to be longer than 5 ns. Although these results present a striking contrast of the spin relaxation time, the long nanosecond spin relaxation time in cubic GaN is consistent with the dependence that spin relaxation time becomes longer for wider-band-gap zincblende semiconductors. The fast picosecond spin relaxations in hexagonal GaN might arise from the unique band structure.

**Raman Scattering Analysis of GaN with Various Dislocation Densities:** Toshio Kitamura; Shin-iti Nakashima; Nayuha Nakamura; Kei Furuta; Hajime Okumura; National Institute of Advanced Industrial Science and Technology; Nihon University; R&D Association for Future Electron Devices International

In this paper, we characterized the GaN crystals with various dislocation densities by micro-Raman spectroscopy. Crystallinity for the GaN layer was examined through measurements of the Raman shift and the width of the E(2)(high), E(2)(TO), and A(1)(TO) phonon bands. The Raman bands in GaN crystals broaden with increasing of dislocation density. The in-plane distribution of strain and crystallinity in epilayers with various dislocation densities was also examined by Raman mapping measurement. The spatial fluctuation of phonon frequency and band width in samples was observed. The magnitude of fluctuation of Raman parameters become large with increase of dislocation density. The increase of dislocation density in GaN epilayers induces not only the broadening of Raman band but also increase of fluctuation.

**Raman Scattering and Cathodoluminescence Characterization of Near Lattice-Matched InAlN Epilayers:** David Pastor; Ramon Casco; Luis Artis; Sergi Hernandez; Oscar Martinez; Juan Jimenez; Robert Martin; Kevin O’Donnell; Ian Watson; Institute Jaume Almera (C.S.I.C.)

Although the InAlN alloy has great potential as efficient barrier in GaN-based devices, data on its optical properties are scarce owing to the difficulty of growing high-quality material. We present cathodoluminescence (CL) and Raman scattering measurements on a set of near lattice-matched InAlN epilayers grown by MOCVD on GaN/sapphire substrates. The Raman spectra show the A(1)(LO) and InN-like E(2) modes of the alloy, whose frequencies are in good agreement with existing model calculations. No noticeable frequency shift of the E(2) modes are observed for the In compositions studied, which suggests pseudomorphological growth of the thin films. The CL spectra exhibit a luminescence peak above the GaN band-edge emission that shifts to lower energies for increasing InN fraction is observed. For the lattice-matched composition, the peak emission is estimated to be about 3.7 eV.

**Raman Scattering Study of B,Ga,N Epilayers Grown by MOVPE on GaN Substrates:** Esther Alarcon-Liado; Ramon Casco; Jordi Ibanez; Luis Artis; Abdallah Ougazzaden; Simon Gautier; Institute Jaume Almera (C.S.I.C.); Georgia Institute of Technology; University of Metz and SUPELEC, Laboratoire Matériaux Optiques, Photonique et Systemes

The demand for ultraviolet laser devices with shorter wavelengths has prompted the investigation of alloying in the group-III nitrides to obtain materials with larger band gaps than that of the GaN. B, GaN is a potential candidate which can be lattice-matched to SiC and AlN if a sufficient amount of boron can be achieved. However, the high lattice mismatch between BN and GaN makes it difficult to obtain B,GaN with an appreciable B concentration. We have studied a set of B,GaN thin films grown by MOVPE with B concentration between 1.1 and 3.6%. Incorporation of B was confirmed by SIMS measurements. XRD measurements reveal an additional peak that shifts with B composition attributed to the alloy. UV Raman scattering measurements show that the A(1)(LO) frequency increases with increasing B composition. Strain relaxation occurs in thick samples leading to a blueshift of the A(1)(LO) mode.

**Recombination Dynamics of Localized Excitons in AlGaN-Based Quantum Wells:** Hideaki Marutani; Takuya Saito; Nobuo Kato; Yoichi Yamada; Tsunemasa Taguchi; Yamaguchi University

We have studied the effect of internal electric field on exciton localization in AlGaN-based quantum wells (QWs) by means of time-resolved photoluminescence (PL) spectroscopy. We observed the averaged time-dependent PL using rate equations and obtained the PL lifetime and the localization time of excitons for three QWs with different well-layer thicknesses. The localization time became longer with increasing well-layer thickness. This result indicates that a quantum confined Stark effect causes the reduction in transition probability of excitons from extended to localized states. In addition, the localization time decreased with increasing excitation density and the three QWs indicated almost the same localization time at higher excitation density. Since the alloy composition is the same for the three QWs, the degree of localization due to alloy disorder does not change so much. Then, we consider that the screening of the internal electric field results in the same localization time.

**Remarkable Enhancement of 254-280 nm Deep UV Emission from AlGaN Quantum Wells by Using High-Quality AlN Buffer on Sapphire:** Toru Yatabe; Hideki Hirayama; Tomoaki Ohashi; Norihiko Kamata; RIKEN; Saitama University

We observed remarkable enhancement of 254-280 nm deep UV emission from AlGaN multi quantum wells (MQWs) by using low threading dislocation density (TDD) AlN templates fabricated on sapphire substrates. High-quality AlN templates were fabricated by using ammonia pulse-flow multi-layer growth method by metal-organic chemical vapor deposition (MOCVD). The screw dislocation density of AlGaN layer on AlN template were 3.5 x 10^7 cm^-2. The photoluminescence (PL) intensity of 278 nm AlGaN-QW emission was increased by approximately 30 times by reducing the full width at half-maximum (FWHM) of X-ray diffraction (XRD) (102) os-canning rocking curve of AlGaN buffer from 1214 to 488 arcsec. The internal quantum efficiency (IQE) of the AlGaN-QW was as high as 30% from the temperature dependence of PL intensity. We also observed the PL intensity enhancement with the reduction of the XRD FWHM for QWs with peak emission wavelength of 254, 260, 270 and 280 nm.

**Scanning Near-Field Optical Microscopy of AlGaN-Based Quantum Wells:** Hideaki Marutani; Nobuo Kato; Takuya Saito; Yoichi Yamada; Tsunemasa Taguchi; Yamaguchi University

We have studied the influence of both localization and internal electric field on the microscopic photoluminescence (PL) properties of AlGaN-based quantum wells (QWs) by means of scanning near-field optical microscopy (SNOM). We measured SNOM-PL images of three QWs with different well-layer thickness under an illumination-collection (I-C) mode and observed the correlation between the PL intensity and the PL peak wavelength. The shorter-wavelength PL indicated the stronger intensity for the wider QW. We consider that the correlation is caused by the inhomogeneous screening of the internal electric field. Under the I-C mode, the screening and the resultant PL blue shift are large at localization centers (local potential minima) as compared with those at local potential maxima. Therefore, we conclude that the correlation becomes prominent when the screening of the internal electric field (blue shift) is larger than the potential fluctuation due to alloy disorder (Stokes shift).
Strain and Defects in AlN Grown with High-Temperature MOVPE: Max Buegler; Ute Haboeck; Ronny Kirsie; Christian Thomsen; Frank Brunner; Arne Knauer; Markus Weyers; Michael Kneisel; Axel Hoffmann; TU-Berlin, Institute for Solid State Physics; Ferdinand-Braun-Institut für Höchstfrequenztechnik

The growth of high quality AlN layers is an essential precondition for deep-UV emitters. To achieve this AlN-epilayers were investigated by means of photoluminescence (PL) and Raman spectroscopy. The samples were grown on sapphire substrates by metalorganic vapor phase epitaxy at temperatures between 1200°C and 1500°C. We observed an emission line near the bandedge at 5.95eV which can be attributed to a donor-bound exciton. Its emission energy depends on the growth temperature. Additionally, Raman spectroscopy shows a significant shift of the strain-sensitive E2(2) mode. Due to the fact that the emission of the bound exciton shows the same behavior as the E2(2), we attribute the shift of the emission to the strain state of the sample. Furthermore, we investigated deep defects in the AlN-epilayers which can also be observed in PL spectra at 3.8eV.

The 3.3eV Band in GaN: Correlation with Defects by CL and TEM Studies: Martin Schirra; Martin Feneberg; Günter Prinz; Rolf Sauer; Klaus Thonke; Thomas Wunderer; Peter Brückner; Ferdinand Scholz; Andrey Chuvilin; Ute Kaiser; Isabel Knoke; Elke Meissner; Universität Ulm, Institut für Halbleiterphysik; Universität Ulm, Institut für Optoelektronik; Universität Ulm, Materialwissenschaftliche Elektronenmikroskopie; Fraunhofer Institut IISB, Erlangen

Non- and semipolar GaN samples frequently exhibit emission bands at 3.3 eV and around 3.41 eV which are believed to be defect-related. We performed a systematic cathodoluminescence (CL) and transmission electron microscopy (TEM) study on selectively overgrown GaN stripes with semipolar [1-101] side facets. Under unfavorable growth conditions these also show intense defect-related bands. Spatially resolved CL spectra allow to assign distinct bands to different regions of the triangularly shaped GaN stripes. Monochromatic CL images reveal, that the 3.3 eV and the 3.41 eV emission originate from the lower part of the triangles, while the bond gap related emission is found on top of the triangles. Defects are identified by TEM images and their influence on the luminescence spectra and maps is discussed in detail.

The CL Emission Observation of the InGaN/GaN MQWs V Shaped Pits with Different Superlattices Underlayers: Wei-Chih Lai; Yu-Shing Chow; Soo Jin Chua; 1National University of Singapore; 2Institute of Materials Research and Engineering

Bulk GaN films are known to contain a high density of defects threading dislocations. These threading dislocations caused formation of V shaped pits on the InGaN/GaN MQWs. In this study we prepared three InGaN/GaN MQWs with different SLs under layers to create different V-shaped pits. The InGaN/GaN MQWs had got wider diameter V-shaped pits and rougher surface if we introduce the SLs under layers. The V shaped pits diameter of sample with SLs under layers is around twice larger than sample without SLs under layers. The grain like emission was seen on the CL spatial images. The samples with SLs under layers showed CL intensity inhomogeneous on the CL spatial images. Moreover we found the light escaped from V shaped pits of InGaN/GaN MQWs with AlGaN/GaN SLs under layers. That might be the key issue to get better efficiency of the light emitting devices.

Thermal Quenching of Luminescence and Isovalent Traps Model for Rare Earth Ions Doped AIN: Wojciech Jadwiesienczak; Henryk Lozykowski; ‘Ohio University

Investigations of luminescent properties of rare earth implanted AlN thin films at temperature in the range 9-800 K are reported. The temperature studies of photoluminescence and cathodoluminescence spectra revealed unexpectedly weak thermal quenching of visible luminescence in Pr, Eu, Gd, Tb, Dy, Tm and Yb-doped AlN samples. Photoluminescence excitation spectra, obtained under UV excitation in the spectral range 200-400 nm, exhibit several bands. It is proposed that the RE ions exist in semiconductors as isolated ions (singlet), nearest neighbors (nm) ion pairs (dimer), and three ions (trimer). The Koster-Slater and simple spherical potential-well models for RE structured isovalent (RESI) hole trap are proposed. The exciton binding energies of RESI traps are calculated and compared with experimental thermal quenching energies. The energy transfer processes between AIN host and 4f-shell systems are emphasized as the main mechanisms for thermal quenching processes rather than nonradiative decay of 4f transitions.

Time-Resolved Photoluminescence Studies of InGaN/GaN Quantum Wells on GaN Homo Substrates: Yue-Due Han; J. G. Park; D. Lee; C. C. Kim; C. S. Kim; Y. H. Choi; M. S. Noh; Chungnam National University; LG Electronics Institute of Technology

Optical properties have been investigated from InGaN/GaN quantum wells (QWs) grown on GaN homo substrates. InGaN QWs are known to have a strong piezoelectric field across wells in addition to strong carrier localization in the well. However, it is difficult to separate these contributions, which is important to understand the mechanism and optimize QW structures for device applications. In order to determine the degree of localization and piezoelectric field in QWs, time-resolved photoluminescence (PL) using a streak camera or time-correlated single photon counting system with a femtosecond laser has been measured in conjunction with excitation power dependence and temperature dependence of PL spectrum. We have found that the carrier lifetime at low temperature, which gives information on the wavelength overlap between electron and hole, is very sensitive to the variation of growth condition and structural change. The results are analyzed together with continuous wave PL and room temperature time-resolved PL.

V-Pits’ Morphologies and the Related Optical Properties of InGaN/GaN Multiple Quantum Wells: A New Insight into Optical Properties: Wen-Jen Liu; Ting-Chin Chiang; Shou-Jinn Chang; 1National University of Singapore; 2Institute of Materials Research and Engineering

The V-pits’ morphology and the related optical properties of InGaN/GaN multiple quantum wells (MQWs) were studied by scanning electron microscopy (SEM); transmission electron microscopy (TEM), and photoluminescence (PL). The InGaN/GaN MQWs with high-density large V-pits were grown by metal organic chemical vapor deposition. It is found that the morphology of the V-pits affects the MQWs’ morphology as well as the recombination mechanism. Three types of MQWs with different facet morphologies were studied, which contribute to three different PL emission bands: 1) the normal c-plane MQWs; 2) the MQWs grown on (10-11) faceted sidewalls, which contribute to a PL band with much higher energy than the c-plane MQW emission band; and 3) the MQWs grown on the [11-2m] (m22) faceted sidewalls, which give a PL band with the energy in between the above two bands.

Very Strong Nonlinear Optical Absorption in Green GaInN/GaN Multiple Quantum Well Structures: Wei Zhao; Mengwei Zhu; Yong Xia; Yufeng Li; Jayantha Senawiratne; Shi You; Theeradetch Detchprouhm; Christian Wetzel; Rensselaer Polytechnic Institute

The efficiency of green GaInN/GaN light emitting diodes (LEDs) is known to drop under high current densities. To explore the reason, 535 nm emitting GaN/GaN multiple quantum well (MQW) and GaN epilayers were characterized using z-scan techniques under comparable excitation conditions with a continuous wave laser. Two wavelengths, 514 nm and 488 nm, were selected right below and above the apparent optical absorption edge. At 514 nm, a very large nonlinear absorption coefficient β = 2.6 cm/W was obtained. This leads to a 20% absorption at a photon flux of 21 kW/cm². We attribute this to nonlinear free-carrier absorption. On the other hand, at 488 nm, a nonlinear saturable absorption with β = 1.7 cm/W was observed. This induced transparency indicates photon bleaching in the MQW. Apparently free carrier dynamics strongly affects optical nonlinearity, while nonlinear absorption provides only a small contribution to the limitations of current green LEDs.
Anisotropic Optical Matrix Elements in Strained GaN-Quantum Wells with Various Substrate Orientations: Atsushi Yamaguchi; 1 Kanazawa Institute of Technology

In-plane optical anisotropies in compressively strained III-nitride quantum wells on semi-polar and non-polar substrates were calculated by using $6 \times 6 k\cdot p$ Hamiltonian. It is shown that the quantum confinement and compressive strain have the opposite effects on the anisotropy. For example, the compressive strain enhances the transition for light polarized to the $c$-axis in quantum wells on non-polar substrates, while the quantum confinement effect enhances the transition for light polarized to the perpendicular direction. Thus, the in-plane polarization degree is determined by the competition of these two effects. These characteristics are also verified by analytical calculations, and it is found that the signs of $(A_x, A_y)$ and $(D_x, D_y)$ are essential factors to determine the above-mentioned polarization properties, where $A_x$ and $A_y$ are valence band parameters and $D_x$ and $D_y$ are deformation potentials. Based on the calculated results, the structural design of laser diodes on semi-polar and non-polar substrates is also discussed.

Energy Relaxation Processes of Photo-Generated Carriers in Mg Doped (0001)GaN and (1-101)GaN: Nobuhiko Sawaki; Jin Saida; Eun Hee Kim; Toshiaki Hikosaka; Yoshih Honda; Masahito Yamaguchi; 1 Nagoya University

The pico-second energy relaxation of photo-generated excess carriers in Mg doped (0001)GaN and (1-101)GaN is studied at room temperature. The samples were grown by MOVPE on a patterned Si substrate. The PL intensity correlation curves showed double exponential decay in high energies, from which we determined fast and slow decay time constants. The slow process on the order of 80-200ps was energy insensitive. At low energies, we found an anti-correlation behavior, which suggests that the accumulation of carriers in the localized centers occurs as the result of the relaxation from high energy states. The fast decay process was observed over a wide energy range and the time constant around 10ps depended on the energy. The fast process was attributed to the potential fluctuation near the valence band edge in the Mg doped GaN.

Growth and Optical Properties of a-Plane AlN and Al Rich AlN/AlGaN Quantum Wells Grown on a-Plane Sapphire Substrate: Talal Al Tahhamouni; Ashok Sedhain; Jingyu Lin; Hongxing Jiang; 1 Kansas State University

Deep ultraviolet (UV) emitters and detectors operating in the 200–340 nm wavelength range have many important applications, including water purification, biological/chemical agent detection and medical care. To realize deep UV emission ($\lambda < 280$ nm), Al-rich AlGaN based QWs are required. The growth of QW structures along the polar direction is characterized by the presence of polarization induced electrostatic fields, which limit the performance of optoelectronic devices that employ QWs as active regions. Growth along nonpolar directions produces nitride-based quantum structures that are unaffected by the strong electrostatic fields. We report on the growth of a-plane AlN epilayer templates and AlN/AlGaN, AlN QWs on r-plane sapphire substrate by MOVCD. Deep UV photoluminescence was employed to study the optical properties of the AlN templates and QWs. A range of well widths for a- and c-plane QWs was investigated, which allows us to identify the emission characteristics that are unique to nonpolar orientations.

High Quantum Efficiency of Semipolar GaN/AlGaN Quantum Wells: Martin Feneberg; Frank Lipski; Martin Schirra; Rolf Sauer; Klaus Thonke; Thomas Wunderer; Peter Brückner; Ferdinand Scholz; 1 Institut für Halbleiterphysik, Universität Ulm; 2 Institut für Optoelektronik, Universität Ulm

The development of efficient GaN/GaN based light emitting devices is hampered by built-in electric fields. These fields, arising from piezoelectric and spontaneous polarization, separate electron and hole wavefunctions and reduce their spatial overlap. Therefore, the internal quantum efficiency is drastically reduced in the presence of built-in fields. To decrease the detrimental influence of the polarization fields on quantum efficiency, growth on non- or semipolar crystal facets is conducted. We investigate samples containing quantum wells grown on the [1-101] facet of selectively overgrown GaN stripes and compare them to samples grown on the commonly used c-plane. By field-dependent photoluminescence we experimentally determined direction and strength of built-in polarization fields. A much weaker field inside the tilted semipolar quantum wells is found (-0.1 MV/cm) compared to structures grown on the polar c-plane (-1.9 MV/cm).

Internal Quantum Efficiency (IQE) and Optical Polarization Analysis of InGaN/GaN Multiple Quantum Wells on a-Plane GaN: Eu-Ying Lin; C. Y. Chen; Tsiong-Sheng Lay; T. C. Wang; J. D. Tsay; 1 National Sun Yat-Sen University; 2 TRI

Internal Quantum Efficiency (IQE) and polarized light emission of non-polar InGaN/GaN MQW grown on a-plane (1120) GaN film were investigated in comparison with polar c-plane (0001) InGaN/GaN LED samples. In the temperature dependence and power dependence PL spectra, the IQE for a-plane and c-plane InGaN/GaN multiple quantum wells were carried out without the time-resolved PL experiment. The a-plane and c-plane InGaN/GaN MQW polarized phenomenon in normal-emitting and edge-emitting PL measurements were also observed and analyzed. The anisotropic structure of quantum wire in a-plane MQW was clearly observed in edge-emitting PL spectrum and TEM.

Optical Properties in Nonpolar a-Plane Strained GaN by Native Gallium Oxide Layer Grown by Photo-Electrochemical Method: Han-Min Wu; Chih-Ming Lai; Lung-Han Peng; 1 National Taiwan University; 2 Ming Chuan University

We report the observation of enhanced green emission centered at 500nm, accompanied with spectral blue shift of 4nm in the UV (360nm) bandedge emission upon a-plane GaN passivated with photo-enhanced wet chemical oxide. The a-plane GaN was grown on the c-plane of sapphire substrate by MOCVD. The polarized micro-PL study was carried out by a pulsed 266nm Nd:YAG laser. The temperature dependent luminescence data reveal an evolution of gain competition between the green and the UV emission bands and at 50K the green emission intensity is larger than that of the UV band by 50%. By dissolving the oxide we resume the emission spectrum of the grown a-GaN. These observations are ascribed to a compressively-strained a-GaN thin surface layer due to the coherently grown gallium hydroxide GaOOH atop that is responsible for the spectral blue shift and the generation of acceptor like deep-levels that result in the enhanced green emission.

Optical Properties of GaN/AlGaN Quantum Wells Grown by Molecular Beam Epitaxy on a-Plane GaN ELO Templates: Amélie Dussaing; Claire Pinquier; Tiankai Zhu; Denis Martin; Nicolas Grandjean; 1 Ecole Polytechnique Fédérale de Lausanne

Non-polar GaN is of great interest due to the possibility of elaborating III-nitride heterostructures without internal electric field. This would allow improving the efficiency of light emitting diodes and lasers. In this work, optical properties of GaN/AlGaN quantum wells (QWs) grown by molecular beam epitaxy (MBE) on a-plane GaN templates are presented. These templates are grown by hydride vapor phase epitaxy using epitaxial lateral overgrowth technique in order to reduce the defect density. GaN/AlGaN single QWs are realized by MBE using ammonia as nitrogen source with various parameters: Al composition (5-20%) and well width (2-8 nm). Micro-photoluminescence (PL) and macro-PL measurements have been performed. Typical full width at half maximum of 30 meV demonstrates high optical quality. The absence of internal electric field is confirmed. Sharp transition energies on the PL peak of the 2 nm-thick Al content QW are ascribed to exciton localization. Their origin will be discussed.

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Optical Properties of High Quality MOVPE Grown Non-Polar a-Plane GaN Epilayers: Alexander Franke; Barbara Bastek; Martin Noltemeyer; Frank Bertram; Juergen Christen; Matthias Wieneke; Armin Dadgar; Alois Krost; Ronny Kirse; Ute Harboeck; Otto-von-Guericke-University Magdeburg, Institute of Experimental Physics; Technical University Berlin, Institute of Solid State Physics

High quality MOVPE grown (11-20) a-plane GaN layers are characterized using photoluminescence (PL) and cathodoluminescence (CL) spectroscopy. The 4K PL spectra show (D, X) emission lines at 3.495 eV as well as (A', X) transitions at 3.482 eV, respectively. Their spectral position corresponds to a compressive stress of 0.9 GPa in quantitative agreement with 0.6 GPa obtained by Raman spectroscopy. The dominating defect emission at 3.42 eV is attributed to basal plane stacking faults (BSF). The s-shape temperature dependence of its peak energy reveals a localization energy of 25 meV. BSF CL-mappings of both, intensity and peak wavelength exhibit a striation contrast with stripes exactly oriented along the (1,1,0,0) direction as quantified in the 2D-spectral density function of the maps. In contrast, the PSF CL-images result in a spotty pattern showing no preferential orientation. CL line scans across adjacent columns shows an alternation of the BSF energy up to 9.94 meV.

Optically Induced Strain Relaxation in Anisotropically Strained M-Plane GaN Films: Timur Flissikowski; Oliver Brandt; Pranob Misra; Holger Grahn; Paul-Drude-Institute

Strained M-plane GaN films, where the c-axis (z-direction) lies in the film plane, can exhibit a very large in-plane polarization anisotropy. For a certain range of in-plane strain values, the wave function of the highest and the second highest valence band (VB) becomes completely |x>-like and |z>-like, respectively. This wavefunction symmetry can be directly observed by spatially resolved photo-reaction spectroscopy, we investigate the local strain in the film. Finally, we found that the tightly focused laser induces a relaxation of the strained film which effects only the direction perpendicular to the c-axis.

Polarization- and Temperature Dependent Photoluminescence and Reflectivity Study of Nonpolar (11-20) GaN: Tobias Guehne; Zahia Bougrioua; Sophie Laügt; Mathieu Leroux; Centre de Recherche sur l’Hétéroépitaxie et ses Applications-CNRS

By use of R (1-102) oriented sapphire substrates, GaN can be grown along the nonpolar [11-20] direction. In these cases, the polar c-axis is not along the growth direction. As a result, QCSE in quantum heterostructures, caused by internal fields originating from interfacial charges, can be annihilated when they are grown on (11-20) GaN templates. We investigate in this work the optical properties of laterally overgrown nonpolar GaN on partially masked (11-20) GaN templates grown by metalorganic vapor phase epitaxy. In conjunction with internal strain components deduced from HRXRD measurements, the transition energies and the oscillator strength of the free excitons are calculated in order to compare them with the experimentally obtained values.

Stimulated Emission from Nonpolar and Polar AlN: Narihito Okada; Kentaro Nagamasu; Motoaki Iwaya; Satoshi Kamiyama; Hiroshi Amano; Isamu Akasaki; Hisaaki Maruyama; Takashi Takagi; Akira Bando; Hideaki Murotani; Yoichi Yamada; Meijo-University; Ibiden Company, Ltd; Showa Denko K.K.; Yamaguchi University

Nonpolar AlN is attracted much attention to realize high-performance UV light emitting devices due to elimination of the internal electric field induced by piezoelectricity in the quantum well. However, experimental evaluation of the advantage of nonpolar plane had been still hindered because of the presence of high-density dislocations and stacking faults in nonpolar AlN layer. We have succeeded to achieve high-quality polar and nonpolar epitaxial lateral overgrown (ELO) AlN layers by high-temperature metal-organic vapor phase epitaxy (HT-MOVPE). In this letter, we report stimulated emission from nonpolar and polar AlN by optical excitation. Then, stimulated emission from nonpolar AlN was confirmed and a threshold excitation power density of nonpolar AlN is almost the same as that of polar AlN both at 8K and 100K.

The Internal Quantum Efficiency Behavior of a-Plane and c-Plane InGaN/GaN MQWs with Different Indium Compositions: Te-Chung Wang; Tsung-Shine Ko; Run-Ci Gao; Tien-Chang Lu; Hao-Chung Kuo; Sing-Chung Wang; Jenq-Dar Tsay; National Chiao Tung University; Industrial Technology Research Institute

Despite many reports about the advantages of non-polar plane had published, it’s still not clear about the IQE behavior for different indium composition/wavelength. According to the theoretical calculation, without the influence of polar effect, the spontaneous polarization field and piezoelectric field both could be eliminated. And there is highly potential to realize high bright light emitting device at blue/green wavelength. For sure the phenomenon, we prepared four groups of samples consist of a-plane and c-plane MQWs with the same geometric MQW structure and with different indium compositions to analysis the IQE behavior. And we find the localized state might enhance the performance of a-plane MQW although the TDD is quite high. This result reveals the potential of a-plane InGaN MQW to high bright blue/green LED. On the other hand, the indium phase separation might also occur on a-plane InGaN MQW so that the intensity decrease and spectrum bandwidth broader.
The electrical properties of InGaN that is either undoped, or Mg doped, are compared to learn about the nature of p-type conductivity. When In alloy fraction beyond 5% is used, Hall measurements indicate a n-type polarity, even when Mg doping is employed. In contrast, hot probe measurements show that p-polarity can be measured for the entire range of Mg-doped In mole fractions. The conflicting polarity indications are the result of surface electron accumulation. Parasitic electron conductivity can further be seen in p-n homojunctions at In fractions including 20% and 30%. This has an impact on structures such as solar cells. Temperature variable conductivity and PL from different layer structures provides further understanding of the nature of InGaN: Mg. P-type InAlN is shown for In mole fractions near 50%.

8:00 AM

BB2, An Experimental Real Time Study of Hydrogen Behavior in InN: Maria Losurdo1; Tong-Ho Kim; Giorgio Pettinari; Antonio Polimeni; Mario Capizzi; Maria Giangregorio; Soojoong Choi; Giovanni Bruno; April Brown; ’Istituto di Metodologie Inorganiche e dei Plasmi-National Research Council; ’Electrical and Computer Engineering-Duke University; ’Universita La Sapienza

The interaction of InN epitaxial films grown by MBE with atomic hydrogen produced by a remote H2 t.f. plasma source is investigated in real time by exploiting spectroscopic ellipsometry. The dependence of InN-H reaction rate on temperature is presented. We found that: a competition between hydrogen incorporation in InN and desorption as NHx exists leading to stable hydrogen inclusion at T<300°C, while hydrogen becomes unstable and desorbs as InHx at T>300°C. Real time ellipsometry data are supported by a photoluminescence study, which provides experimental evidence that hydrogen acts as a donor in InN: the electron concentration increases upon sample hydrogenation and decreases with post-hydrogenation thermal annealing at 300°C. Optical spectra as a function of annealing time and temperature indicate that hydrogen-related donors occupy two stable equilibrium sites, and diffuse out from the samples with two characteristic activation energies, whose values have been determined.

9:15 AM

BB3, Improvement of the Surface Morphology of a-Plane InN Using Low-Temperature InN Buffer Layers: Go Shikata; Shigeru Hirano; Takeru Inoue; Misao Orihara; Yasuto Hikikata; Hiroyuki Yaguchi; Sadafumi Yoshida; ’Saitama University

We report on the improvement of the surface morphology of a-plane InN films grown by RF molecular beam epitaxy using low-temperature (LT) InN buffer layers. Although the surface of InN films grown without LT-InN buffer layers was rather rough, we could successfully obtain InN films with a smooth surface by using LT-InN buffer layers. The full width at half maximum values of the X-ray diffraction (11-20) rocking curve were 2800 arcsce and 4700 arcsce for a-plane InN samples grown at 500°C with and without LT-InN buffer layers, respectively. Thus, we could improve also the crystalline quality of a-plane InN films by using LT-InN buffer layers. Strong photoluminescence was observed at ~0.63 eV, which is lower than the PL peak energy for c-plane InN films. This red shift is probably due to the Franz-Keldysh effect.

9:30 AM

BB4, Real-Time Observation of Spontaneous, Cyclic Growth and Decomposition of InN during MOVPE: Fan Jiang; Anneli Munkholm; Ruey-Yen Wang; Kujimi Latifi; Carol Thompson; Ken Elder; Paul Fussl; Costas Dimitropoulos; Stephen Streiffer; Gregory Stephenson; ’Argonne National Laboratory; ’Philips Lumileds Lighting Company; ’Northern Illinois University; ’Northern Illinois University; ’Oakland University

We have been using real-time synchrotron x-ray scattering and fluorescence as in situ probes to study growth of InN and InGaN by MOVPE. In this talk we report that MOVPE of InN on GaN can be inherently unstable, spontaneously cycling between growth and decomposition. Under constant input flows of NH3 and trimethylindium (TMI) at temperatures in the range 550-675°C, we observe a cyclic process: epitaxial islands of crystalline InN nucleate and grow to micron size; the InN islands collectively decompose into liquid In droplets; the liquid In evaporates; and another cycle of InN growth begins. These results will be discussed in terms of a model in which the effective nitrogen activity produced by catalytic decomposition of NH3 on the surface depends on the amount of InN and In liquid present.

9:45 AM

BB5, Etching and Optical Deterioration of Nitrogen-Face of Wurtzite InN in NH3 Ambient: Akio Yamamoto; Ken ichi Sugita; Yasuhiko Nagai; Akiiho Hashimoto; ’University of Fukui

We describe the etching and optical degradation of N-face of wurtzite InN in the NH3 ambient at around 600°C. Both In- and N-polar InN films with a thickness about 0.5 μm are grown on (0001) sapphire with the atmospheric-pressure MOVPE. After the growth, InN samples are annealed at 500-650°C for 2-6 h in the NH3 flow (6 slm). The InN samples are etched by the annealing and the etching rate of the N-face is found to be three times higher than that of the In-face. For both In- and N-polar films, the N-face shows a larger PL peak shift to the higher energy side that the In-face, showing that a high density of donor-type defects are preferentially introduced on the N-face of InN. Such instability of N-face in the NH3 ambient seems to be related to the poorer quality of MOVPE InN.

10:00 AM

BB6, The Importance of Reducing Strain for the Improvement of Crystalline Quality of MOVPE InN: Ken-ichi Sugita; Akiiho Hashimoto; Akio Yamamoto; ’University of Fukui

This paper reports the c-lattice parameter dependence of tilt and twist fluctuations for MOVPE InN. Using an atmospheric-pressure MOVPE system with a horizontal reactor, InN films are grown on GaN or Al1-xOx(0001) templates or directly on α-Al2O3(0001) using a low temperature GaN buffer. Growth temperature is varied from 450 to 650°C. The c-lattice parameter is increased with increasing growth temperature. Since the c-lattice parameter for strain-free is reported to be 5.703 Å, the result obtained here shows that, with increasing growth temperature, the strain is changed from tensile to compressive at a temperature around 550°C. A clear correlation exists between c-lattice parameter and tilt and twist fluctuations. It is found that the minimum values for both tilt and twist fluctuations are obtained for the strain-free c-lattice parameter. This means that the reduction of strain is very important to improve the crystalline quality of MOVPE InN.

10:15 AM

BB7, The Growth and Characterization of InN Layers Grown by High-pressure CVD: Nikolaus Dietz; Mustafa Alevli; Ramazan Atalay; Goksel Durkaya; William Fenwick; Hun Kang; Ian Ferguson; ’Georgia State University; ’Georgia Institute of Technology

The successful integration of InN and indium-rich group III-nitride layers into wide band gap group III-nitrides, is a fundamental step enabling envisioned emerging device structures, such as high-efficient spectral agile white LED’s, radiation hardened magneto/optoelectronics, spectral tailored detectors, or advanced device structures for high speed optoelectronics and optical communication. This contribution will present results on the growth and real-time characterization on InN layers grown by a novel high-pressure chemical vapor deposition (HPCVD) system, which as been developed at GSU. The HPCVD system is capable to control the vast different partial pressures of the constituents for reactor pressures up to 100bar. Single-
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crystalline InN layers grown at growth temperatures of 850°C and reactor pressures around 15 bar are of high structural quality with XRD FWHM better than 400 arcsec, demonstrating that the chosen HPCVD pathway works. Selected results on the structural and optical properties of grown InN films are presented.

10:30 AM  Break

Session CC:
Nonpolar and Semipolar Materials and Devices IV
Thursday AM  Room: 313/316  Location: MGM Grand Hotel Conference Center
September 20, 2007

8:30 AM  Invited
CC1. Progress of Nonpolar m-Plane InGaN/GaN Laser Diodes: Konyoshi Okamoto; Hiroaki Ohta; Shigeoasa Chichibu; Taketoshi Tanaka; Testuhiro Tanabe; Hidemi Takasu; ROHM Company, Ltd.; Tohoku University

Continuous-wave operation of nonpolar m-plane violet InGaN/GaN laser diodes (LDs) has been realized by using m-plane GaN homoepitaxial substrates. The LDs had almost no stacking faults and macroscopic cracks, and their performance was already comparable to that of conventional c-plane violet LDs. A distinct characteristic of nonpolar LDs was the strong anisotropy of the photon emission, according to the polarization selection rules for anisotropically strained InGaN quantum wells. As a result, the threshold current density (4.0 kA/cm²) of the LDs whose ridge stripe was parallel to the c-axis was lower than that of a-axis stripe LDs. We will show such unique characteristics of m-plane LDs and our recent works on optimizing the device structure and the growth conditions for longer wavelength m-plane LDs.

9:00 AM
CC2. AlGaN-Cladding-Free Nonpolar InGaN/GaN Laser Diodes: Mathew Schmidt; Daniel Feezell; Robert Farrell; Makoto Saito; Kenji Fujito; Daniel Cohen; James Speck; Shuji Nakamura; Steven DenBaars; University of California at Santa Barbara

We demonstrate a nonpolar m-plane GaN laser diode that does not contain any AlGaN cladding layers for optical waveguiding. The ability to grow thick quantum wells (~8 nm) on m-plane GaN leads to sufficient optical confinement without the need for AlGaN claddings. Broad area lasers were grown by metal organic vapor deposition (MOVCD) on bulk m-plane GaN substrates and fabricated using etched facets. Threshold current densities as low as 2.3 kA/cm² were observed. AlGaN-cladding-free nonpolar GaN-based laser diodes offer several advantages over conventional c-plane GaN-based lasers. The presence of thick AlGaN cladding layers can be detrimental to device performance by increasing the series resistance, operating voltage, operating temperature, and threshold current density. Thick AlGaN layers, or high Al-content AlGaN layers, lead to cracking issues, as well. Employing an AlGaN-cladding-free design can have a significant impact on both improving device performance and manufacturability.

9:15 AM
CC3. Non-Polar AlxGa1-xN Multiple Quantum Well Deep UV LEDs over Bulk m-GaN: Balakrishnan Krishna; Vinod Adivarahan; Thomas Katona; R.S. Farade; Bin Zhang; Asif Khan; University of South Carolina, Electrical Engineering; Photonics Microelectronics Laboratory


9:30 AM
CC4. Fabrication of GaInN MQW LED with Low Defect Density on m-Plane SiC Substrate: Takeshi Kawashima; Takeshi Hayakawa; Masako Hayashi; Tetsuya Nagai; Daishuke Iida; Aya Miura; Yoshinosh Kamasatsu; Motoaki Iwaya; Satoshi Kamiyama; Hiroshi Amano; Isamu Akasaki; Meijo University

One of problems of realizing high-efficiency green light emitting devices is the large internal electric fields, such as the spontaneous polarization and piezo-electric field. Using a nonpolar plane, the piezoelectric filed is suppressed. In this study, we report the fabrication of m-plane GaN multiple quantum well (MQW) LED with low defect density on m-plane SiC. Low-defect-density GaN films on m-SiC was grown by the sideline epitaxial lateral overgrowth (SELO) technique. A periodic grooved structure in which the terrace was covered with SiOz mask was fabricated by reactive ion etching and conventional photolithography. The stripe direction was <1-100>. A GaN layer was grown from the sidewall of a seed GaN. As a result, we succeeded in growing low-defect-density m-plane GaN. We fabricated m-plane GaN MQW LED on SELO-grown GaN film. The light output power of LED on SELO-grown GaN was about 50 times stronger than that on non-ELO GaN.

9:45 AM
CC5. InGaN/GaN Laser Diodes on Semipolar (10-11) Bulk GaN Substrates: Anurag Tyagi; Hong Zhang; Roy Chang; Daniel Feezell; Makoto Saito; Kenji Fujito; James Speck; Steven DenBaars; Shuji Nakamura; University of California, Santa Barbara; Mitsubishi Chemical Corporation

The first semipolar nitride laser diodes (LDs) have been realized on low extended defect density semipolar GaN bulk substrates. The LDs were grown by conventional metal organic chemical vapor deposition (MOCVD). Broad area layers were fabricated and tested under pulsed conditions. Lasing was observed at a duty cycle of 0.025% with a threshold current density (Jth) of 18 kA/cm². An output power of 18 mW was measured from a single facet of the device at a drive current of 1.2 A, with the calculated differential quantum efficiency (ηdiff) being 15%. Stimulated emission was observed at 405.9 nm with a narrow full width half maximum (FWHM) of less than 0.3 nm.

10:00 AM
CC6. InGaN-Based LEDs Grown by Plasma-Assisted MBE on (0001) Sapphire with GaN QDs in the Nucleation Layer: C. Thomidis; A. Nikiforov; Tao Xu; Theodore Moustakas; Boston University

Blue-violet LEDs based on InGaN MQWs were grown by RF-plasma MBE on (0001) sapphire with GaN QDs incorporated in the nucleation layer as a mechanism of dislocation filtering. Devices with dimensions 800 μm x 800 μm were fabricated and evaluated at a constant current configuration by measuring their EL spectra and power output. At low injection current, the EL spectra peak at 440 nm. At high injection current a second peak at 385 nm becomes the dominant one and it is attributed to tunneling of injected electrons through the electron layer. The dependence of the power output as a function of the injection current was studied systematically in order to evaluate the effects of heating. Power outputs up to 9 mW were measured at the injection current of 1 A.

10:15 AM
CC7. Growth of Non-Polar a- and m-Plane GaN by Ammonia Molecular Beam Epitaxy: Eric Young; Melvin McLaurin; Feng Wu; Tom Mates; James Speck; University of California at Santa Barbara

Non-polar orientations of the III-V wurtzite nitrides are currently of interest due to their potential in eliminating polarization discontinuities and improving the efficiency of nitride-based light emitters. In this work, we demonstrate growth of non-polar a-plane (11-20) and m-plane (1-100) GaN by ammonia molecular beam epitaxy (MBE) on r-plane sapphire and m-plane SiC, respectively. Films were determined to be of high epitaxial quality and
showed anisotropic surface morphologies and structural properties consistent with a high stacking fault density. The surface morphology of m-plane GaN was strongly dependent on growth conditions, showing small islands at low growth temperatures and smooth, slate-like morphology with abrupt terraces at higher growth temperatures and V/III ratios. Mg incorporation at concentrations between 8x10^10 and 6x10^18/cm^2 was also achieved for m-GaN films, a promising result towards achieving devices by ammonia MBE.

10:30 AM Break

Session DD:
Engineered Properties of GaN by MOVPE Growth

Thursday AM
Room: 314/315
Location: MGM Grand Hotel Conference Center

08:30 AM
DD1, Fabrication of a GaN p/n Lateral Polarity Junction by Polar Doping Selectivity: Ramon Collazo1; Seiji Mita1; Anthony Rice1; Rafael Dalmaui2; Zlatko Sitar2; North Carolina State University

The difference in surface energy between the Ga-polar orientation and the N-polar orientation of GaN translates into a completely different behavior for the incorporation of intentional and unintentional impurities. Oxygen is found to be an impurity with higher concentration in N-polar films than in Ga-polar films and is the cause for the high carrier concentration observed in N-polar films. We fabricated a lateral p/n junction in GaN by the simultaneous growth of p- and n-type regions, utilizing the doping selectivity of the two different polar domains, which resulted in an n-type carrier concentration of 1.7x10^19 cm^-3 with an electron hall mobility of 99 cm^2/Vs in the N-polar domains, and a p-type carrier concentration of 1.1x10^19 cm^-2 with a hole hall mobility of 12 cm^2/Vs in the Ga-polar domains. These junctions showed the characteristics that define a p/n junction: current rectification, electroluminescence, and photo-effect.

08:45 AM
DD2, Electrical Characterization of p-Type N-Polar GaN Grown by Metalorganic Chemical Vapor Deposition: Nicholas Fichtenbaum1; Chris Schanke1; Tom Mate1; Christine Cobb1; Stacia Keller1; Steven DenBaars1; James Speck1; Umesh Mishra1; University of California, Santa Barbara

We report on Mg-doped N-polar and Ga-polar GaN films grown by MOCVD. The bis-cyclopentadienyl magnesium (Cp2Mg) flow was varied between 64 and 640 nmol/min, for N-polar and Ga-polar samples, while other growth conditions were held constant. The sample surfaces were characterized by atomic force microscopy (AFM). Electrical measurements were made to determine the resistivity, specific contact resistance, carrier concentrations, mobilities, and activation energies. N-polar samples exhibited a minimum resistivity of 1.6 Ωcm while Ga-polar samples had a minimum resistivity of 1.2 Ωcm. Hall effect measurements revealed hole concentrations and mobilities of 5 x 10^17 cm^-3 and 4 cm^2/Vs for the N-polar and 6 x 10^17 cm^-3 and 13 cm^2/Vs for the Ga-polar. Temperature dependent measurements revealed an activation energy of 105 meV for N-polar and 108 meV for the Ga-polar. Finally, current-voltage measurements were used to characterize the properties of N-polar p-n diodes as a function of the Cp2Mg flow.

09:00 AM
DD3, Impact of Ultra-Low Nucleation Density on GaN Film Dislocation Density: Daniel Koless1; Stephen Lee1; Michael Coltrin1; Gerald Thaler1; Karen Cross1; Sandia National Laboratories

For improved GaN films on sapphire, GaN nucleation layers (NLs) are typically used prior to high temperature growth. Recently, a correlation between the nucleation density and the GaN film dislocation density has been suggested. However, from the available studies it is difficult to determine the strength of this correlation and the extent that reduced nucleation density can be used to achieve lower dislocation density films. Recently, we have initiated studies of ultra-low (< 107 cm^-2) nucleation densities on sapphire using multi-step NL growth and annealing schemes. We find that the nucleation density correlates directly with the thickness of the first NL and subsequent NL growth and annealing cycles only add to the nuclei volume. A simple geometric model for dislocation generation will be presented to explain the power law behavior of the dislocation density on the nucleation density for dislocation generation primarily along tilt boundaries or in random arrays.

09:15 AM
DD4, Metal Organic Chemical Vapor Deposition of N-Polar GaN Films on Vicinal Substrates: Stacia Keller1; Nicholas Fichtenbaum1; Feng Wu1; David Brown1; Angel Rosales1; Steven DenBaars1; James Speck1; Umesh Mishra1; University of California, Santa Barbara

Smooth, high quality N-polar GaN films with treading dislocation densities comparable to Ga-polar GaN films were obtained by MOCVD on misoriented sapphire substrates. While MOCVD growth of Ga-polar (Al,Ga,In)N has been widely studied in the past, the investigation of N-polar films and heterostructures was hampered by the poor surface morphology often observed for MOCVD grown films caused by the formation of hexagonal hillocks. In this presentation we will show, that the hillock formation can be prevented through growth on vicinal sapphire substrates. With increasing misorientations the structural and optical quality of the N-polar GaN films significantly improved, and the properties of GaN grown on 4 deg off substrates were comparable to Ga-polar GaN films (XRD: FWHM (002) = 300 arcsec, FWHM (101) = 480 arcsec). The influence of the sapphire nitridation, the nucleation layer, and main layer growth conditions on the film properties will be discussed.

09:30 AM
DD5, Selective Area Growth of GaN on Patterned Sapphire Substrates by Metalorganic Vapor Phase Epitaxy for Highly Efficient UV Light Emitting Diodes: Katsuyuki Hoshino1; Masahiro Araki1; Kazuyuki Tatamoto1; Yamaguchi University

We have successfully obtained high-quality GaN films on patterned sapphire substrates (PSSs) by utilizing selective area growth (SAG) and epitaxial lateral overgrowth (ELO) without any mask. The dislocation density reached a value as low as 8 x 10^7 cm^-2. We have also fabricated a LED. The output power and external quantum efficiency of the LED operated at 20 mA were 22.7 mW and 40.4%, respectively. GaN films were grown on PSSs having striped grooves. The growth in the ridge region was suppressed by controlling both growth temperature and H/(H2+N2) ratio, resulting that the SAG in the groove region was performed. After the SAG, both the ridges and grooves were buried completely under the GaN layer by utilizing ELO. The growth technique developed here is very effective in reducing the dislocation density and increasing the extraction efficiency in the LEDs because of the light scattering at the patterned GaN/sapphire interface.

09:45 AM
DD6, Late News
10:00 AM
DD7, Late News
10:15 AM
DD8, Late News
10:30 AM Break
Technical Program

Session EE:
InN Heterostructures and Quantum Wells

Thursday AM
September 20, 2007
Location: MGM Grand Hotel Conference Center

11:00 AM
EE1, Structural Quality Improvement in 1 ML InN/GaN Quantum Wells Using Bulk-GaN Substrate: Hideyuki Saito; Song-Bek Che; Kazuaki Matsumura; Naoki Hashimoto; Eun-Sooon Hwang; Xinqiang Wang; Yoshihiro Ishitani; Akihiko Yoshikawa; 1Chiba University

Ultra thin InN well (~1ML) insertion in GaN matrix has been demonstrated recently. This novel InN nano-structure is potentially applicable to room-temperature operating excitonic devices. In this structure, very flat surface/ interface quality is required because the quantum well thickness is only 1ML. The samples reported in Ref.1, however, had relatively high density threading dislocations (TDs) more than 10^15 cm^-2 because MOVCD-GaN templates grown on sapphire were used. Generally, in MBE-GaN growth on the templates, hexagonal growth spiral hillocks are observed on their surface and these are correlated to the TDs, which seriously affect flatness of the 1ML InN well. In this study, to improve structural perfection in the InN(1ML)/GaN QWs, low dislocation density bulk-GaN substrates (TDD ~10^5 cm^-2) were used. Superior interface and structural quality was obtained and fine 1ML InN well formation was achieved even for a single QW structure grown on bulk-GaN. 1A.Yoshikawa et al., APL 90, 073101 (2007)

11:15 AM
EE2, Study on “One-Monolayer InN” Epitaxy Process on Ga-Polarity GaN Template: Effects of GaN Matrix on Epitaxy Temperature and Self-Limiting Thickness of In-Polarity InN: Naoki Hashimoto; Song-Bek Che; Hideyuki Saito; Eun-Sook Hwang; Xinqiang Wang; Yoshihiro Ishitani; Akihiko Yoshikawa; 1Chiba University

Recently, we have demonstrated successful fabrication of novel structure InN/GaN MQWs consisting of 1-ML-thick InN wells inserted in GaN matrix by RF-MBE1. Here, atomically flat-sharp In-polarity InN wells were coherently grown at such high temperatures up to 650°C on the basis of 1) self-ordering process arising from immiscibility nature between InN and GaN, and 2) effectively increased In-N bonding by the GaN-matrix effect. In this paper, in order to clarify the detailed mechanism on 1ML InN deposition on Ga-polarity GaN, in-situ and real time monitoring by both RHEED and spectroscopic ellipsometry of InN epitaxy processes on Ga-polarity GaN were performed. It was shown that the deposition of InN is self-limited so that the thickness is around 1-ML (up to a few-MLs) and following InN deposition was stopped by its reevaporation at such high temperatures of 650°C for In-polarity InN epityax. 1A. Yoshikawa et al., Appl. Phys. Lett. 90, 073101 (2007)

11:30 AM
EE3, Optical Emission Properties of InN/In0.53Ga0.47N Multi-Quantum Wells on Bulk-GaN Substrates: Songbek Che; Xinqiang Wang; Yoshihiro Ishitani; Akihiko Yoshikawa; 1Graduate Course of Electrical and Electron Engineering, Venture Business Laboratory, InN-Project as a CREST-program of JST, Chiba University; 1InN-Project as a CREST-program of JST, Chiba University

InN/In0.53Ga0.47N multi-quantum wells are key materials for the development of nitride-based near-infrared optical devices. In order to realize LEDs or LDs with the MQWs, investigation of their optical properties such as light-emission efficiency is important. In this study, InN/In0.53Ga0.47N MQWs were grown on bulk-GaN substrates (TDD ~10^5 cm^-2) because superior optical properties and clearer dependence on InN well thickness (0.5~1.5nm) compared with that on sapphire were obtained. By comparing the experimental results with theoretical calculations and considering lattice relaxation behavior in the MQW region, we found that when the InN well thickness is less than 1nm, which corresponds to the critical thickness in the MQWs, drastic increase in PL intensity is observed. This is mainly caused by minimizing piezoelectric effect in thinner InN well samples.

11:45 AM
EE4, Intensity-Dependent Photoluminescence Studies of the Electric Field in In-N-Face and In-Face InN/InGaN Multiple Quantum Wells: Grace Chern; Eric Readinger; Hongen Shen; Michael Wraback; Gregor Kohlmuller; Chad Gallina; James Speck; 1US Army Research Laboratory; 1University of California, Santa Barbara

We probe the electric field in In-face and N-face InN/InGaN multiple quantum wells (MQWs) using low temperature intensity-dependent photoluminescence (PL) under continuous-wave laser excitation at 900nm. The In-face structure consists of 30 periods of 2.5nm thick InN wells and 24nm thick In0.92Ga0.08N barriers. The N-face sample consists of 25 periods of 1.5nm InN wells and 15nm thick In0.88Ga0.12N barriers. At low excitation power, the PL peak energy from both In-face and N-face MQWs is redshifted relative to that from bulk InN. As excitation power increases, we observe a 50 and 44meV blueshift of the PL peak energy from the In-face and N-face MQWs, respectively. The blueshift is a result of the optically induced screening of the built-in electric field. From the measured blueshift, we calculate a minimum change of the electric field to be ~0.4MV/cm and ~0.6MV/cm in the In-face and N-face well regions, respectively.

12:00 PM
EE5, Growth and Characterization of InN/GaN Heterojunctions by MBE: Kejia (Albert) Wang; Debdeep Jena; 1University of Notre Dame

In this work, the growth of InN on GaN by MBE has been studied. High quality InN was achieved by optimizing the substrate temperature and the III/V flux ratio. Structural quality was characterized by X-ray diffraction measurements, and Hall measurements of a 1.8nm thick InN sample shows high electron concentrations (~3e18 cm^-3) and high room-temperature mobilities (~1500 cm^2/Vs). Optical measurements including absorption and photoluminescence show that the bandgap of grown InN is ~0.7eV. A strong correlation is found between the structural and transport properties of the InN. The band offset of InN and GaN was measured through a C-V intercept-method measurement. Taking into account the effect of the interface polarization dipole, the conduction band offset between InN and GaN was extracted to be around 1.5 eV.

12:15 PM
EE6, Atmospheric-Pressure MOVPE Growth of In-Rich InAlN: Yoshihori Houchin; Akio Hashimoto; Akihiro Yamamoto; 1University of Fukui

We report the atmospheric-pressure MOVPE growth of In-rich InAlN. An InAlN is grown on a nitrided (0001) sapphire at 600-700°C in the pressure of 730 Torr. The incorporation of In in InAlN is increased with increasing growth temperature. An increase in In content is also observed for films grown at a position farther from the up-stream end of the susceptor. Such an increase in In, i.e., a decrease in Al incorporation can be explained by the parasitic reaction of TMA with NH3. A single-crystalline InAlN film with an In content of 1-0.55 is successfully grown by adjusting growth temperature and TMI/TMl (TMA) molar ratio. FWHM of X-ray rocking curve for InAlN is increased with decreasing In content. The carrier concentrations in InAlN films are comparable to that in InN (1-5 × 10^18 cm^-3). All the single-crystalline InAlN films with an In content of 1-0.7 show a photoluminescence at room temperature.

12:30 PM
EE7, Late News

12:45 PM
EE8, Late News
11:00 AM Invited
FF1, III-Nitride Nanowires and Networks: Growth, Heterostructures, Epitaxial Alignment, and Applications: Jung Han; Shigefusa Chichibu; Hong Tang;1 Yale University; Tohoku University

Most of NWs are prepared by catalytic VLS method on amorphous or polycrystalline substrates. The as-grown, hay-stack like NWs are dispersed randomly onto target wafers, where electrical contacting and/or characterizations are performed. The purpose of this paper is to demonstrate a hybrid approach toward the construction of GaN NW arrays and networks through the use of (optical) lithographically-defined selective-area growth (SAG) and bottom-up VLS synthesis. Spatially ordered and flexibly patterned NW networks are prepared, in which the stochastic nature in contemporary process of NW synthesis and fabrication is greatly mitigated. While we anticipate a new paradigm rendered by this novel and more deterministic fabrication process in pursuing NW-based electronic and photonic applications, we will focus in this talk on the nanomechanical characterizations of ordered NW arrays to demonstrate the possibility of a new direction in NW research, complementary and orthogonal to the existing nanoelectronic and nanophotonics.

11:30 AM
FF2, Growth and Characterization of Vertically Aligned III-Nitride Nanowires: George Wang; Qiming Li; A. Alec Talin; J. Randall Creighton; Elaine Lai; Fabien Arslan; Richard Anderson; Donald Werder; Sandia National Laboratories; Los Alamos National Laboratory

Nanowires based on the direct bandgap semiconductor Group III nitride (AlGaN) materials system have attracted attention as potential building blocks in optoelectronics, sensing, and electronics. We have employed a VLS-based metal-organic chemical vapor deposition process to synthesize highly aligned arrays of single-crystalline GaN nanowires on sapphire substrates without the use of a patterned template. The effects of growth time, temperature, and catalyst preparation were found to have strong effects on the ordered growth and will be discussed. The optical and electrical properties of the nanowires were studied and show a strong correlation with the growth temperature, which we propose is due to carbon incorporation from the metal-organic source. Building on our growth technique, aligned radial heterostructure nanowire arrays were synthesized and characterized using 3D STEM imaging. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under contract DE-AC04-94AL85000.

11:45 AM
FF3, Near-Infrared Intersubband Emission from GaN/AlN Quantum Dots and Quantum Wells: Laurent Nevov; Francois Julien; Maria Tchernycheva; Fabien Guillot; Eva Monroy; 1Equipe mixte CEA-CNRS-UJF Nanophysique et Semiconducteurs, DFRMC/SP2M/PSC

We report on the observation of intersubband (ISB) luminescence at 300 K from GaN/AlN quantum dots (QD) and quantum wells (QW) in the wavelength range of 1.5 to 2.3 μm. All samples have been grown by plasma-assisted molecular beam epitaxy on AIN/sapphire templates. Under optical excitation at λ=1.34 μm, the GaN/AlN QD superlattice exhibits emission at λ=1.5 μm ascribed to the pz-s intraband transition of electrons. This phonon-assisted process provides room for population inversion. We next report on QW samples containing 2.1 nm thick GaN wells with 3 nm thick AlN barriers. The active region is designed to exhibit three bound states in the conduction band. Under optical pumping resonant with the e1-e3 transition (λ=0.98 μm), ISB emission corresponding to the e3-e2 transition is observed at λ=2.1 (2.3) μm for heavily (lightly) doped QWs. Prospects for ISB lasers using nitride QWs or QDs will be discussed.

12:00 PM
FF4, GaN/AlGaN Nanocolumn Ultraviolet Light Emitting Diodes on N-(111) Si Substrates Grown by RF-Plasma Assisted Molecular Beam Epitaxy: Hiroto Sekiguchi; Shunsuke Ishizawa; Koki Sakamoto; Goh Kobayashi; Jo Tanaka; Kei Kato; Akihiko Kikuchi; Katsumi Kishino; Sophia University

Self-organized nitride nanocolumns which has 20~200 nm in diameter have grave potentiality for high performance light emitting diodes in UV to NIR region due to their dislocation-free nature and high light extraction efficiency. In this study, the room temperature operation of surface-connection type GaN/AlGaN nanocolumn-UV-LED was demonstrated for the first time. The nanocolumn UV-LED was grown on n-type (111) Si substrate by rf-plasma assisted molecular beam epitaxy as a sequence of n-GaN, n-Al0.25Ga0.75N nanocolumns, 3-periods GaN/Al0.25Ga0.75N multiple quantum disk active region, n-Al0.35Ga0.65N nanocolumn, p-Al0.25Ga0.75N and p-GaN. For the p-type region, we increased nanocolumn diameter to connect the neighboring nanocolumns, consequently surface of the nanocolumn LED became continuous film. The electroluminescence (EL) of the nanocolumn UV-LED was observed through a Ni/Au semi-transparent p-electrode (500μm). The peak wavelength was 354 nm with the FWHM of 29.3 nm. But the small area observation (50μm) showed narrower FWHM of 12.0 nm.

12:15 PM
FF5, Optical Properties of High Quality Factor GaN/AlN Microdisks: Dobri Simeonov; Eric Feltin; Hans-Jörg Bühmann; Stephanie Mattei; Julien Dorsaz; Jean-François Carlin; Raphael Butté; Nicolas Grandjean; École Polytechnique Fédérale de Lausanne (EPFL)

Microdisk structures attract much attention owing to their potential for fabricating low-threshold lasers and for studying cavity quantum electrodynamics phenomena such as strong light-matter coupling or the Purcell effect. We present here the fabrication of mushroom-like microdisk structures containing InGaN/GaN quantum wells (QW), using the lattice-matched GaN/AlN system. A selective lateral wet chemical etching technique of the previously oxidized AlInN interlayer is used to optically isolate the cavity from the underlying GaN template. Whispering-gallery modes with quality factors (Q) exceeding several thousands (Q>3200) are observed. We demonstrate that this value is absorption limited and genuine values of Q~6000 at QW transparency are reported. Low threshold lasing action at room temperature is equally obtained. FDTD simulations provide a detailed understanding of the microdisks’ optical properties. A close comparison of these optical properties to those previously reported for inverted cone structures highlights the versatility and adaptability of such 3D microcavities.

12:30 PM
FF6, C-Axis GaN Nanowires for High-Quality-Factor Mechanical Oscillators: George Wang; Qiming Li; A. Alec Talin; J. Randall Creighton; Elaine Lai; 1École Polytechnique Fédérale de Lausanne (EPFL)

We report on the electromechanical properties of c-axis GaN nanowires in high-quality-factor mechanical resonators and closed loop oscillators. The GaN nanowires are grown by catalyst-free molecular beam epitaxy, are single crystal, typically hexagonal in cross section, from 50-100 nm diameter, and 5-15 microns in length depending upon growth time. Such nanowires have masses in the picogram range. The nanowires display singly-clamped cantilever mechanical resonances above 1 MHz, with typical resonance full width at half maximum power of less than 100 Hz i.e., a mechanical quality factor, Q, well above 106. We use piezoelectric drive and scanning electron microscope detection of nanowire motion to observe closed loop GaN nanowire oscillators with Q above 106. We will discuss using these oscillators as sensors, demonstrating mass detection sensitivities below 10^-18 grams in a 1 second averaging time. Temperature dependences and observed noise properties will be discussed.
Technical Program

12:45 PM
FF7, Electrical Defect and Transport Properties of a Single GaN Nanorod P-N Junction Diode: Young Park1; Chang M. Park1; Bo Ra Hwang1; Hyeunil Im1; H. Y. Cho2; T. W. Kang3; M. S. Son3; K. H. You4; 1Dongguk University; 2Yonsei University

The electrical properties of a single GaN nanorod p-n junction diode were characterized by the temperature-dependent current-voltage and deep level transient spectroscopy measurements. The p-n junction nanorods were patterned on a SiO2 substrate by using e-beam lithography. In order to confirm the formation of p-n junction, cathodoluminescence and current-voltage measurements, as a function of temperature, were made. The current-voltage curve exhibits strong temperature dependence, suggesting that thermionic emission over a barrier dominates. This barrier most likely corresponds to emission from a deep level in the band. The deep level appears to be an electron trap at Ec=0.40 eV below the conduction band with a capture cross section of 2.22x10^-16 cm2 per the depletion region of the p-n junction.

11:00 AM Invited
GG1, Origin of Defect-Insensitive Emission Probability in (Al,In,Ga)N Alloy Films Containing In: Shigefusa Chichibu1; 1Tohoku University

Group-III nitride semiconductors (Al,In,Ga)N have shown enormous potential as light sources for full-color displays, traffic signals, and solid-state lighting. Remarkably, InGaN blue- and green-LEDs fabricated on c-plane (0001) sapphire substrates emit brilliant light although the threading dislocation density generated due to lattice mismatch is six orders of magnitude higher than that in conventional (Al,In,Ga)(As,P) amber, red, and IR LEDs. In this presentation, we explain why three-dimensional (3D) bulk (Al,In,Ga)N films containing In exhibit a defect-insensitive emission probability. From the results of time-resolved PL and positron annihilation measurements, the nonradiative recombination process in GaN will be shown to be governed by certain defects introduced with the incorporation of Ga. In order to enlighten the role of threading dislocations (TDs) on the improvement of crystal quality of InGaN quantum well is important to the understanding of electronic and optical properties of InGaN quantum wells.

11:30 AM
GG2, Luminescence Lifetime in the Vicinity of Threading Dislocations on Bulk GaN Studied by Picosecond Time Resolved Cathodoluminescence (pTRCL): Samuel Sonderegger1; Jelena Rist1; Pierre Cordf1; Eric Feltn1; Nicolas Grandjean1; Benoit Devcaud1; Jean-Daniel Ganière1; 1EPFL

In order to enlighten the role of threading dislocations (TDs) on luminescence properties of GaN and nitride based heterostructures, radiative and non-radiative lifetimes in the vicinity of and on TDs have been studied by recently demonstrated picosecond time resolved cathodoluminescence (pTRCL) both in bulk GaN and InGaN/GaN quantum wells. The studied GaN ELOG samples comprise up to 10^8 TDs per cm^2. Individual TDs resolved at a temperature of 100K by quasi continuous cathodoluminescence appear as correlated dark spots on the surface. First results show a 25% decrease of effective lifetime when changing the excitation spot from a dislocation free zone onto a dislocation (42 ps down to 30 ps). This variation is most probably due to the decrease of the non-radiative lifetime meaning that non-radiative recombination becomes predominant when approaching a dislocation. Ongoing studies by pTRCL on InGaN QW are aimed at quantifying the influence of TDs on luminescence properties.

11:45 AM
GG3, The Influence of Dislocations on Optical Properties of InGaN-Cathodoluminescence and Transmission Electron Microscopy of Layers Grown on Miscut GaN Substrates: Martin Albrecht1; Thilo Remmele1; Tadeusz Suski1; Gijs Franssen2; M. Krzy2; B. Lucia3; I. Gergery1; Piotr Perlint; Wielawyl Porowski1; 1Institute of Kristallzüchtung, 2Institute of High Pressure Physics ‘Unipress’, Polish Academy of Sciences

We present results from spectral cathodoluminescence mappings and Z-contrast transmission electron microscopy analysis of MOVPE grown InxGaN-xN layers (nominally x=0.1). GaN substrates with miscut from 0.3 to 3 deg were used. CL spectral maps show a terrace structure formed of (0001) and [11-1m] facets by distinct CL emissions. The (0001) and [11-1m] facets show CL bands at 3.05 eV and 3.15 eV respectively. According to Z-contrast images the difference in emission is caused by different In contents.

With increasing miscut the total area of (0001) facets reduces, while the area of [11-1m] facets leading to a blue shift of the integral CL. Samples grown on dislocation free substrates do not show terraces and a homogeneous CL. We discuss the difference in optical properties as dependent on miscut and dislocations density in terms of dislocation induced step bunching and kinetics in incorporation kinetics into different microfacets.
Technical Program

Thursday PM

Session HH:
InN: Surface and Electronic Properties

Thursday PM
Room: 312/317
Location: MGM Grand Hotel Conference Center

2:30 PM Invited
HH1, Surface Properties of InN and In-Rich Alloys: Tim Feat; 1University of Warwick

One of the most striking properties of InN is its extreme surface electron accumulation. Angle-resolved synchrotron radiation photoemission spectroscopy of InN surfaces has been used to map the dispersion of the quantized subbands in the surface potential well, enabling the energies of the subband minima and the subband electron effective masses to be determined. Additionally, using high-resolution x-ray photoemission spectroscopy (XPS), the surface Fermi level, and therefore the surface electron accumulation, has been found to be the same for both In- and N-polarity InN. Core-level XPS of clean InN surfaces indicates termination by In-adlayers: 3.4 ML and 2.0 ML of In on the surface of In- and N-polarity InN, respectively. Based on first principles calculations, the In-In bonds in the surface In-adlayers have recently been associated with the donor-type surface states responsible for the intrinsic electron accumulation. Studies of the surfaces of p-type InN and In-rich alloys are also reported.

3:00 PM
HH2, Effect of Surface States on Electrical Characteristics of InN and In-GaN: Joanne Yin; 1R Jones; 2K M. Yu; 3J. W. Ager; 4W Walukiewicz; 5J Wu; 6J. Schaff; 7University of California - Berkeley; 8Lawrence Berkeley National Laboratory; 9Cornell University

Surface states are known to pin the Fermi level in InN and In-GaN, strongly affecting charge distribution and transport on the surface and interfaces. By solving Poisson’s equation in an electrolyte-based capacitance-voltage measurement configuration, we have calculated the band bending and space charge distribution in this system and developed an electronic model generally applicable to both p- and n-type nitride thin films. Both conduction band non-parabolicity and band renormalization effects due to the high surface electron concentration were included. The calculated space charge distributions, using the majority dopant concentration as a fitting parameter, are in excellent agreement with experimental data. The model quantitatively confirms increasingly strong n-type electrical characteristics on the surface due to electron accumulation in p-type In-GaN for decreasing values of x.

3:15 PM
HH3, Study on Surface Electron Accumulation on A-Plane InN by Electrolyte-Based Capacitance-Voltage Measurements: Mitsukio Noda; 1Shinji Fukumoto; 2Daisuke Muto; 3Kin Man Yu; 4Nic Miller; 5Joel Ager II; 6Eugene Hailer; 7Hiroyuki Naoi; 8Taotomu Araki; 9Yasushi Nanishi; 10Wladek Walukiewicz; 11Ritsumeikan University; 12Lawrence Berkeley National Laboratory

InN is a promising material for applications in long wavelength optical devices and high-speed and high-frequency electrical devices owing to its outstanding material properties. In order to fully utilize the potential of InN, it is important to understand the surface and interface properties of InN. It is well known that an electron accumulation layer exists at the surface of polar C-plane InN, making it very difficult to form a Schottky junction and thus hindering the research and development of this material toward electronic device applications. On the other hand, the absence of the electron accumulation layer was theoretically predicted for non-polar InN surfaces. The experimental results we obtained from electrolyte-based capacitance-voltage (ECV) measurements, however, imply that an electron accumulation layer also exists at the surface of non-polar A-plane InN. We will report these results, and compare them to those obtained from polar C-plane InN grown by MBE under similar conditions.

3:30 PM
HH4, Control of Electron Concentration in In-Face InN: Chad Gallinat; 1Gregor Kohlmueller; 2James Speck; 3University of California at Santa Barbara

We studied the effect of growth conditions and Si- and Mg-doping on the electrical conduction of In-face InN films grown by plasma-assisted molecular beam epitaxy. Growth temperatures in the range of 420 °C - 480 °C offered control over the electron concentration within the range of -2 x 10^{17} e/cm^3 - 2 x 10^{18} e/cm^3 while maintaining high electron mobilities and optimized structural quality. To achieve electron concentrations higher than 2 x 10^{18} e/cm^3 Si-doping was necessary. Relatively high electron mobilities (>1500 cm^2/Vs) were maintained at the lowest Si concentrations while increasing the electron concentration into the low 10^{18} cm^{-3} range. To decrease electron concentrations as low as 3 x 10^{16} cm^{-3} Mg-doping was employed to compensate the high UID electron concentrations. Through the use of Mg-doping, variable growth temperature and Si-doping the electron concentration was accurately controlled over the range ~3 x 10^{16} cm^{-3} - 5 x 10^{18} cm^{-3}.

3:45 PM
HH5, N-Face InN Multiple Carrier Transport: Tamara Fehlberg; 1Gregor Kohlmueller; 2Gilberto Umaña-Membreño; 3Chad Gallinat; 4James Speck; 5Brett Nener; 6Giacinta Parish; 7University of Western Australia; 8University of California, Santa Barbara

N-face indium nitride samples were grown on C-face SiC substrates via plasma-assisted molecular beam epitaxy using a GaN buffer layer. The
Technical Program

temperature (20 - 300 K) and film thickness (500 - 2000 nm) dependence of multiple carrier transport has been measured via multiple magnetic field Hall measurements. Surface and bulk electron properties were extracted using a quantitative mobility spectrum analysis. Bulk electron mobility shows a clear temperature dependence, with a steep increase with temperature up to the peak mobility, a maximum well over 3000 cm²/Vs at about 100 K in the thickest samples. Bulk electron concentrations are around 2 × 10¹⁷ cm⁻³.

Bulk and surface mobilities increase with sample thickness. Surface electron mobilities are over twice those of In-polar InN, with only a slight reduction in surface concentration. The temperature dependence of both bulk and surface mobilities are significantly different to that of all In-polar samples previously studied.

4:00 PM

HH6, GaN and InN Conduction Band States Studied by Spectroscopic Ellipsometry at Finite Temperatures: Christoph Cobet; Munise Rakel; Christoph Werner; Rüdiger Goldhahn; Norbert Esser; 1 Institute for Analytical Sciences; Technische Universität Ilmenau

We apply spectroscopic ellipsometry in the spectral range between 18-20eV in order to study the conduction bands in GaN and InN. In this spectral range the optical response is defined by excitations of localized core d-electrons to empty states. The imaginary part of the measured dielectric function is thus proportional to the conduction band density of states (DOS) with dominant p-symmetry. Further more, we can assign distinct maxima in dielectric function to specific transitions at high symmetry points in the Brillouin zone. In the presented work we compare e.g. the results for GaN- and InN, which reveal a surprisingly high agreement in respective DOS. A special attention is assigned to temperature effects on the DOS. By comparing the temperature evolution of excitation features measured between 18 and 20eV with those measured among the interband transitions at lower energies, we can study temperature shifts of valence and conduction band states separately.

4:15 PM

HH7, Conduction Band Nonparabolicity and Band Filling in InN under Hydrostatic Pressure: Tadeusz Suski; Izabela Gorczyca; Gijs Franssen; Agata Kaminska; N. E. Christensen; A. Svane; Andrijez Suchocki; H. Liu; W. J. Schaaff; E. Iliopoulos; A. Georgakilas; 1 Polish Academy of Science, Institute of High Pressure Physics; Polish Academy of Science, Institute of Physics; 2 University of Aarhus, Department of Physics and Astronomy; 3 Cornell University, Department of Electrical and Computer Engineering; 4 FORTH, Institute of Electronic Structure and Lasers

The low value of about 0.7 eV of the InN band gap leads (via pronounced interaction between conduction band and valence band) to a low effective electron mass m* and a nonparabolic shape of the conduction band. The external pressure causes the band gap to increase and influences the conduction band nonparabolicity. This leads to significant effects of pressure and band filling on m* and the photoluminescence (PL) peak energy EPL. This was proved through experimental and theoretical studies. The PL peak pressure coefficient dEPL/dp is shown to depend on the electron concentration in accordance with ab-initio calculations. It decreases from about 27 meV/GPa to about 21 meV/GPa on the increase of electron concentration from 3.6 × 10¹⁷ to 1.1 × 10¹⁸ cm⁻³.

4:30 PM Break
grown by MOVPE. ISB wavelength reported so far for crack-free GaN/AlN MQW structures on AlN templates and obtained absorption at 0.78 eV, which is the shortest ISBT absorption for ultra thin wells. Thus, we have grown GaN/AlN MQWs short period GaN/AlN MQWs grown on GaN templates experience critical transitions in III-nitride multiple (M) QWs is investigated. Strain dependence of GaN/AlN quantum wells (QWs). In this work, the effect of strain on ISB in the telecom range is enabled thanks to the high conduction band offset in III-nitride semiconductors. The possibility of obtaining ISBT devices operating at the surface causes decreasing conductivity in InN at the surface of the nanocolumns and remains constant above. In contrast, reconstruction in order to avoid artifacts due to the way to relevant improvements of the performances of GaN based devices. The samples have been grown by metalorganic vapor phase epitaxy (MOVPE) optimizing the deposition conditions and strongly reducing the Al fluctuations in the barriers. This leads to a photoluminescence (PL) broadening of only 5 meV at T= 10 K for an Al content in the barriers of 5%. The biexciton binding energy is found to be of the order of 9 meV. The recombination kinetics show that the exciton and biexciton components are not thermalized at low temperature allowing to extract the intrinsic lifetime of the two components (which is a novelty with respect to GaAs based nanostructures where biexcitons have been extensively studied).

3:45 PM
II6, Space Charged Region in GaN and InN Nanocolumns Investigated by Atomic Force Microscopy: Morton Niebeschütz; Volker Cimalla; Oliver Ambacher; Torsten Machleidt; Jelena Ristic; Javier Grandal; Miguel Angel Sanchez-Garcia; Enrique Calleja; Institute of Micro- and Nanotechnologies, Technische Universität Ilmenau; 2Department of Computer Graphics Program, Technische Universität Ilmenau; IFSOM-Department Ingeniería Electrónica, ETSI Telecomunicación, Universidad Politécnica

High quality InN and GaN nanocolumns of different length and diameter grown by molecular beam epitaxy (MBE) were electrically characterized directly and non-destructively by Atomic Force Microscopy (AFM) as a function of the column diameter. The “exact” column diameter was determined from AFM images by Blind Tip Estimation (BTE) and subsequent image reconstruction in order to avoid artifacts due to the finite AFM tip radius. In GaN the conductivity rise up to a “critical” diameter due to a depletion region at the surface of the nanocolumns and remains constant above. In contrast, the accumulation layer at the surface causes decreasing conductivity in InN nanocolumns with increasing diameter. Thus, the nanocolumn surface acts as the preferential conduction path. These facts prove that there is electron accumulation in as-grown non-polar InN surfaces, according to calculations of the Fermi level pinning in InN.

4:00 PM
II7, Local Electrode Atom Probe (LEAP®) Analysis of GaN-Based Structures: Peter Clifton; Stephanie Gerstl; Mark Galfrey; David Larson; Diane Zhu; Clifford McAleese; 1Imago Scientific Instruments; 2University of Cambridge

The use of Atom Probe Tomography (APT) for the atomic-scale analysis of metallic alloys is well established, but the specimen shape and conductivity requirements have typically limited the application of the technique for the analysis of semiconductor materials. With the advent of commercial laser atom probe instruments and the focussed-ion-beam (FIB) lift-out techniques for specimen preparation, LEAP® has developed into a powerful technique for analysis of semiconductor nanostructures. Offering the combination of high spatial resolution (sub-nm in all three dimensions) and chemical sensitivity (~ 10 ppm detection limits), APT is the only technique that can meet the layer-morphology and interface-chemical-diffuseness characterisation requirements necessary for GaN-based quantum well (QW) type structures. The development of this application will be described, key areas such as specimen preparation will be explained and example datasets will be shown. It is found that GaN-type QW structures are well suited to atom probe analysis.

4:15 PM
II8, Thermal Suppression of Relaxation Bottleneck in a GaN Microcavity: Flavian Stokker-Cheregi; Anna Vinattieri; Marcello Colocci; Fabrice Semondi; Mathieu Leroux; Jean Massies; Ian R. Sellers; Massimo Gurioli; 1University of Florence; 2CRHEA-CNRS; 3University of Buffalo

We present an experimental study aimed to discuss the presence of a phonon bottleneck in a λ/2 GaN bulk microcavity at different temperatures. Time resolved measurements show a very fast lifetime (3 ps) suggesting a major role of non-radiative channels in the polariton recombination kinetics. In order to determine the presence of a relaxation bottleneck, angular photoluminescence (PL) measurements were performed at different temperatures for large negative detuning. At low T the PL shows a marked maximum, at the angle corresponding to the resonance between the exciton and the photon modes, which is an experimental demonstration of the presence of a relaxation bottleneck. Thus, a strong relaxation bottleneck is observed at low T in our microcavity. Suppression of the bottleneck is found when increasing the temperature, denoting a very strong polariton-phonon scattering, also in connection with the very short exciton lifetime.

4:30 PM Break
2:45 PM
JJ2, Direct Observation of Indium Compositional Fluctuation in GaInN/GaN Multi-Quantum Wells Using an X-Ray Micro-Beam of the 8-GeV Storage Ring: Takao Miyajima; Shigeki Uemura; Yoshihiro Kudo; Yasuko Terada; Noriyuki Fuutagawa; Sony Corporation; 3Japan Synchrotron Radiation Institute

GaN-based optical devices demonstrate high quantum efficiency even though there are threading dislocations with high density of $10^{10-12}$ cm$^{-2}$. This unusual situation can be explained by a model related to indium compositional fluctuation. In this model, the indium composition at any threading dislocation is lower than in the surrounding region. Although this model is supported by time-resolved PL and SNOM results, there are few reports of the direct observation of the indium composition around threading dislocations. We succeeded to observe the amount of indium contents' fluctuation in a 50nm x 30nm region of annealed Ga$_{0.9}$In$_{0.1}$N/GaN MQWs by measuring the indium’s fluorescent x-ray excited by a 1.38nm x 3.8m x-ray micro-beam. In the mapping, there are the island-shaped regions which clearly coincide with the low-radiative regions observed by Hg-lamp excited fluorescent microscopy. The indium contents in the island-shaped regions are 20% less than in the surrounding region.

3:00 PM
JJ3, Lattice Polarity Determination for GaN by Modulation Spectroscopy: Ryuji Katayama; Hironori Yaguchi; Kentaro Onabe; University of Tokyo;

A novel polarity-determination method for GaN using modulation spectroscopy is demonstrated, which requires only simple optical setups and is a non-destructive investigation. The method is based on the capability of modulation spectroscopy for the assignment of the electric-field direction. Under the usual case of relatively small residual strains and electron densities, a strong spontaneous polarization induces an upward band-bending toward Ga-polar surfaces, and a downward but weaker bending toward N-polar surfaces. The above difference in band profiles between Ga- and N-polarity GaN films grown by rf-MBE could be distinguished in terms of the flip of the spectral phases, utilizing the different modulation mechanisms between photoreflectance and electoreflectance. Further quantitative lineshape analysis revealed that the excitonic contribution for Ga-polar surface is much smaller than the other. It is interpreted as a field-induced exciton dissociation at a high-field region, expected from the band profile derived as a self-consistent solution of Poisson-Schrödinger equation.

3:15 PM
JJ4, Characterization of Pseudomorphic Al$_x$Ga$_{1-x}$N Layers on Bulk AlN Substrates: Leo Schroeder; Joseph Smart; Wayne Liu; Robert Bondokov; Ken Morgan; Gregory Garrett; Anand Sampath; Hongen Shen; Michael Wraback; Crystal Is, Inc.; Army Research Laboratory

High Al-concentration Al$_x$Ga$_{1-x}$N can be grown on c-face (Al polarity) AlN substrates from bulk crystals with threading dislocation densities or order 10 cm$^{-2}$ or less. For this study, 0.5μm-thick Al$_x$Ga$_{1-x}$N layers were grown on AlN substrates. The FWHM of XRD rocking curves of both the symmetric and asymmetric peaks on the epitaxial layers were typically 60° or less. The layers were pseudomorphically strained to the AlN substrate even though the layer thicknesses exceeded the Matthew-Blakeesee critical thickness by more than an order of magnitude. Photoluminescence showed a peak at about 250nm with a linewidth of 130meV at RT which decreased to ~80meV at 11K while the intensity increased 400 fold. The time-resolved PL showed lifetimes between 100 and 200ps. These results indicate high quality but the low threading dislocation density is not limiting the lifetime allowing other non-radiative decay mechanisms to be studied.

3:30 PM
JJ5, Mechanisms for Enhanced Quantum Efficiency of InGaN Quantum Wells Grown on InGaN Underlayers: Mary Crawford; Daniel Koleske; Nancy Missert; Stephen Lee; Michael Banas; David Follstaedt; Katherine Bogart; Gerald Thaler; Karen Cross; Yong Xia; Christian Wetzel; E. Fred Schubert; Sandia National Laboratories; Rensselaer Polytechnic Institute

Recent reports have demonstrated that the growth of InGaN quantum wells (QWs) on low-temperature InGaN underlayers enables dramatic enhancement of QW photoluminescence (PL). These underlayers (ULs) may impact a range of materials properties, including controlled nucleation of V-defects that interact with overlying InGaN QWs. We have performed spectroscopic studies to elucidate the mechanisms by which ULs enable this striking luminescence enhancement. These studies included analysis of InGaN QWs on ULs of different compositions and thicknesses, as well as different growth temperatures to control V-defect formation. Temperature-dependent and time-resolved PL and cathodoluminescence studies revealed that underlayer composition is a critical parameter, with the addition of only 2.5% indium in the UL providing >6X enhancement of internal quantum efficiency. Study of QWs on ULs grown at various temperatures further revealed that the decoration of threading dislocations by V-defects is the non-dominant mechanism for PL enhancement.

3:45 PM
JJ6, Growth by MOVPE of AlGaN/GaN Structures with Intersubband Transitions in the 1.2-1.7 μm Region of the Spectrum: Matthew Hallsall; Ben Sheriker; Mark Sherwin; Paul Harrison; Peter Parbrook; Tao Wang; University of Manchester; University of California; University of Leeds; University of Sheffield

We report the growth of very small period superlattices of Al$_x$Ga$_{1-x}$N/GaN with high aluminium content (x=0.7) designed to have intersubband transitions in the wavelength range 1.3-1.5μm. The sample parameters were calculated using a self-consistent solution, aiming to achieve a cl-e2 transition at 1.54 μm. In order to achieve large intersubband energies via MOVPE growth a high aluminium content was adopted and very thin 1nm–1.2nm thick GaN layers were attempted. Infrared absorption measurements show clear intersubband transitions at 1.5 μm. The absorption lines are significantly narrower than those reported by other groups. The improved growth quality allows the observation of the cl-e3 transition at 1.18 μm, the shortest wavelength intersubband transition yet reported. The application of such transitions to ultra-fast communications will be discussed along with the recent improvement of nitride growth technology which makes the realization of a 1.5μm intersubband laser a real possibility.

4:00 PM
JJ7, Optical Properties of Near Lattice-Matched GaN/AlN Quantum Wells: Ray Theng Tan; Robert Martin; Kevin O’Donnell; Zhihao Wu; Fernando Ponce; Ian Watson; 4Strathclyde University; 4Arizona State University

Al$_x$In$_{1-x}$N opens up a wide range of important applications as it covers an extremely large energy gap range and, most importantly, can be lattice-matched to GaN. This work describes a series of near lattice-matched GaN/Al$_x$In$_{1-x}$N single quantum wells, grown on both free-standing GaN and sapphire substrates by MOVPE, and studied using photoluminescence spectroscopy and transmission electron microscopy. TEM micrographs confirm the high crystalline quality and reveal the lower quantum well interface to be considerably sharper than the upper one. PL spectra show luminescence originating from the wells, barriers and underlying GaN buffer layers and highlight differences between growth on FS-GaN and sapphire. A near linear dependence of the quantum well transition energy on the well-width is demonstrated to result from intense in-built spontaneous polarisation fields, whose screening is illustrated using power dependent PL measurements. PLE data provide further information on the near-lattice-matched Al$_x$In$_{1-x}$N barrier layers.

4:15 PM
JJ8, Luminescence/Excitation Spectra of Eu-Implanted AlGaN: Ke Wang; Katharina Lorenz; Paul Edwards; Ben Hourahine; Ian Watson; Eduardo Alves; Kevin O’Donnell; Robert Martin; Strathclyde University; 3TTN, Sacavém, Portugal

Photoluminescence and photoluminescence excitation spectroscopy of europium-implanted Al$_x$Ga$_{1-x}$N alloys, over the full composition range from $x = 0$ to 1, reveal significant changes in the spectral pattern of the main $^7F_0$—$^5D_2$ transition. The peak of the Eu spectral multiplet shifts from 621.7 nm for GaN:Eu to 624.4 nm for AlN:Eu. For GaN:Eu, there are two luminescent Eu centres, only one of which can be excited by a broad excitation band lying below the GaN bandgap. Above 16% AlN, the spectral pattern of Al$_x$Ga$_{1-x}$N:
Eu simplifies and red-shifts. PLE spectra feature the AlGaN band-edges and reveal broad below-gap excitation bands. The PL excited below and above gap has the same spectral pattern. We conclude that the Eu luminescence from AlGaN:Eu is from a single Eu site, analogous to that excited in GaN:Eu by below-gap excitation. A strong influence of the AlN content on the emission intensity of AlGaN:Eu is also described.

4:30 PM Break

Poster Session IV
Thursday, 5:00-6:00PM
Room: Prefunction Area
Location: MGM Grand Hotel Conference Center

Devices

AlGaN-Based Deep UV Photodiodes with 330 nm Spectral Cutoff: Thomas Katona; Vinod Adivarahan; Shamima Afroz; Bin Zhang; Asif Khan; University of South Carolina

We report on AlGaN-based deep UV photodiodes that exhibit a gain of 20 under 310 nm illumination. The photodiodes have a peak spectral response at 310 nm with a FWHM of approximately 20 nm. These devices are among the first photovoltaic photodiodes exhibiting gain to be fabricated with an AlGaN active region. Devices were grown on sapphire substrates using pulsed atomic layer epitaxy (PALE), and conventional MOCVD growth. Pulsed AlN buffers and strain management superlattices were grown to reduce the defect density resulting from AlN/sapphire heteroepitaxy and to allow for growth of a thick buffer template of approximately 3.0 μm of Al0.5Ga0.5N. Circular mesa geometry photodiodes were fabricated with device sizes ranging from 20 μm to 100 μm in diameter. The diodes exhibited room-temperature dark currents below 0.5 picoamps at reverse bias exceeding 20 Volts. The dark current increased gradually above -20 Volts with gain observed at -140 Volts.

AlGaN-Based High Power 280 nm Light Source: Yuri Bilenko; Alex Lunev; Igor Shturm; Jianping Zhang; Xuhong Hu; Remis Gaska; Sensor Electronic Technology, Inc.

We report our latest results in developing high power deep ultraviolet light sources based on AlGaN LEDs. The sources consisted of multi-chip arrays with up to 64 LED chips integrated with high power packages for efficient heat extraction. Multi-chip arrays were mounted on top of heat sinks with built-in thermo-electrical coolers which allowed extraction of up to 3.5 W of heating power with LED temperature increase less than 40°C. Deep UV sources were tested in CW and pulse operation modes with current pulse widths of 20-40 ns. Sources with peak emission at 282 ± 2 nm wavelength delivered up to 40 mW of CW output optical power at 600 mA current. In pulsed regime the maximum output power was 290 mW at 5.5 A current. This is the highest output power reported for sub-300 nm semiconductor light sources.

Device Self-Heating Effects in Deep UV LEDs Studied by Systematic Variation in Pulsed Current Injection: Meredith Reed; Michael Wraback; A. Lunev; Y. Bilenko; X. Hu; A. Satta; J. Denga; M. Shatalov; R. Gaska; Army Research Laboratory; Sensor Electronic Technology, Inc.

SET, Inc. 280nm LEDs were studied under various DC and pulse conditions to demonstrate the impact of self-heating associated with nonradiative recombination on the output power and lifetime of the devices. A reduction in output power occurs as the pulse width and duty cycle are increased. For 1μsec pulse width the output power is saturated at currents decreases from 30nmW to 4mW as the duty cycle is increased from 1% to 50%, while for 100μsec pulse width, the output power at saturation current decreases from 10nmW to 3.5μmW for the same range of duty cycle. In both cases, the output power at 50% duty cycle approaches that of the DC conditions, indicating that self-heating has a significant impact on the device performance. Lifetime testing at 100mA was performed under DC and pulse conditions of 100μsec and 1% duty cycle, with half-lives of 20 hours and 1400 hours, respectively.

Double Heterostructure Ultraviolet Light Emitting Diodes with Nanometer Scale Compositionally Inhomogeneous Active Regions: Anand Sampath; Meredith Reed; Gregory Garrett; Eric Readinger; H. Shen; Michael Wraback; Chris Chu; Noble Johnson; Alexander Usikov; Oleg Kovalenkov; Lisa Shapovalova; Vladimir Dimitriev; US Army Research Laboratory; Palo Alto Research Center; Technologies and Devices International

We report the growth, fabrication and evaluation of double heterostructure UVLEDs operating at wavelengths below 325nm that employ a bulk (80nm) AlGaN active region containing nanoscale compositional inhomogeneities (NCI), deposited by plasma-assisted molecular beam epitaxy. The devices were deposited on AlGaN templates grown by hydride vapor phase epitaxy and containing electron and hole injection layers grown by metalorganic chemical vapor deposition. Wafer level measurements of 324 nm LEDs show an output power of 0.43mW for DC drive current of 100mA, while 310nm LEDs show an output power of 0.12mW under similar bias. Time-resolved photoluminescence decays are consistent with the electroluminescence data. These results are comparable to those of conventional multiple quantum well-based devices, which indicates that polarization fields delterious to wave function overlap in conventional double heterostructure devices of similar active layer thickness are mitigated in NCI AlGaN.

Double Band Deep Ultraviolet AlGaN Photodetectors: S. Ashkan; Miko; D. E. Pugel; D. Franz; H. Jones; B. Guan; Jianping Zhang; R. Gaska; NASA/Goddard Space Flight Center; Sensor Electronic Technology

We report on the fabrication and testing of bias-controlled dual band AlGaN-based deep UV back-illuminated photodetectors. A two-terminal n-p-n photo-transistor-like structure consisting of 47% n-AlGaN, 20% p-AlGaN, p-GaN and top contact layer of n-GaN was grown on sapphire substrates by MOCVD. When a forward bias is applied between the top electrode and the bottom electrode, the detector detects light with wavelength longer than 320 nm (UV-A spectral range) and reject UV-B light with wavelengths in the range from 280 nm to 320 nm. The maximum quantum efficiency in this operation regime is in the range from 320 nm to 360 nm. Under reverse bias these devices detect UV-B and reject UV-A. The maximum quantum efficiency shifts to the spectral range from 280 nm to 320 nm. We will present detailed characterization results of the photodetectors, which can separate UV-A and UV-B using the same pixel by bias switching.

Enhanced Light Extraction Efficiency in Flip-Chip GaN Light-Emitting Diodes with Nanotextured Indium-Tin Oxide/Ag Reflectors: Ji-Yeon Kim; Min-Ki Kwon; Il-Kyu Park; Dong-Min Jeon; Je Won Kim; Yong-Chun Kim; Seong-Ju Park; Gwangju Institute of Science and Technology; Samsung Electro-Mechanics Company

We report on the Ag reflector deposited on nanotextured indium-tin oxide (ITO) in flip-chip light emitting diodes (FCLEDs). The nanotextured ITO
Technical Program

was fabricated by wet etching process using a buffered oxide etch (BOE) solution at various ITO etching time of 5, 7, and 10 sec. The FCLED with a nanotextured ITO/Ag reflector etched for 3sec showed an excellent adhesion, thermal property, and higher light-output power of 161.3% at an injection current of 300 mA compared to that with a flat ITO/Ag reflector. This result was attributed to an increase of surface area of nanotextured ITO and increase of probability of reflection of light on the roughened interface between Ag and nanotextured ITO layers.

Enhanced Performance in Ultraviolet Light-Emitting Diodes with Patterned ZnO Transparent Conducting Oxide: Jue-Hong Lim; Min-Suk Oh; Ja-Yeon Kim; Dong-Min Jeon; Je Won Kim; Yong-Chun Kim; Seong-Ju Park; Gwangju Institute of Science and Technology; Samsung Electro-Mechanics Company

The effect of patterned gallium oxide-doped ZnO (GZO) layers on the electrical and optical property of ultraviolet light-emitting diodes (LEDs) is reported. GZO films were deposited on Ni/Au p-type contact layer by pulsed laser deposition, and then the GZO layer was patterned by etching in a 1 wt% HCl aqueous solution. The GaN-based LEDs with patterned GZO layers showed forward voltages similar to Ni/Au p-contact, and this was attributed to that the ohmic contact to p-GaN is mainly formed by Ni/Au p-contact layers. The optical output power of the LED with patterned GZO layers exceeded that of an LED with Ni/Au contact to p-GaN by over 20%. The increase in optical output power of LEDs with patterned GZO layers can be attributed to a small difference of refractive indices between GaN and GZO.

Enhancement of Light Extraction in GaN LEDs Using Photonic Crystals and Index Guiding Layers: Kelly McCroddy; Aurelien David; Michael Iza; Elison Matioli; Shuji Nakamura; James Speck; Claude Weisbuch; Evelyn Hu; University of California, Santa Barbara

GaN has become the prominent material for blue-green light emitting diodes (LEDs). The limiting factor to achieving the high efficiencies needed is the external efficiency due to poor extraction of the emitted light from the device. This work has realized the importance of an integrated optimization of the device structure by using 2D photonic crystals (PCs) in-plane and index guiding layers in the vertical direction to emit most of the LED light into specific guided modes which can be efficiently extracted by the PC. To optimize this effect, PC LEDs with PC lattice constants of 185 nm to 600 nm and depths of 120 nm and 250 nm have been fabricated on material structures with various thicknesses and compositions of AlGaN layers. The effects on the emission properties, measured experimentally by angular-resolved photoluminescence, will be reported. Additionally, the various processing and design challenges will be discussed along with the electrical characteristics of the devices.

Fabrication and Characterization of Integrated Colloidal Quantum Dot and Porous GaN Structures: Seol Baek; Yong-Hwan Kim; Yong-Hoon Cho; Chungbuk National University

Colloidal quantum dots (QDs) were used on GaN based structure to fabricated white light emitting diodes (LEDs) by using color conversion technique. We investigated optical propertied of QDs on different surface shape between nonporous and porous n-type and p-type GaN layers. Porous structure on n-type and p-type GaN layers was formed by wet etching process. The QDs on each substrate were deposited by spin coating technique. For studying optical properties, photoluminescence and confocal microscope measurements were carried out. Two separated peak of GaN and QDs were clearly found in PL spectra at room temperature. The GaN emission intensity was reduced after deposition of QDs. From the confocal microscope measurement, we found the QDs emission was uniformed on non-porous surface but the emission was concentrated only pore region on porous surface.

Gallium Nitride LEDs Incorporating Organic Semiconductor Heterojunctions: Hyunjin Kim; Qiang Zhang; Cuong Dang; Yoon-Kyu Song; Arto Nurminen; Brown University

We have investigated the physical integration of organic thin film semiconductors with GaN-based device structures, to explore new types of “hybrid” heterojunction device structures. In particular, planar hybrid nitride-organic junctions have been shown to be quite versatile in enabling charge injection and excitation transfer across the two very different electronic material constituents. In one device configuration, we have replaced the conventional thermally processed p-type metallization contact to a blue InGaN MQW LED by an organic hole injector layer, α-NPD, deposited on the nitride device structure at room temperature. The L-I-V characteristics of the LED are nearly comparable to those of a fully inorganic reference device, with current densities up to about 20 A/cm². The rationale for these types of structures is the monolithic integration to nitride devices of complementary organic devices, such as for compact biosensors.

GaN Vertical n-p Junctions Prepared by Si Ion-Implantation: Martin Kosec; Gilberto Umana-Membreno; Felix Recht; Azlan Baharin; Nicholas Fichtenbaum; Lee McCarthy; Stacia Keller; Roberto Menozzi; Umesh Mishra; Giacinta Parish; Brett Nener; School of Electrical, Electronic and Computer Engineering, University of Western Australia; Department of Electrical and Computer Engineering, University of California, Santa Barbara; Department of Information Technology, University of Parma

We report on vertical n-p junctions formed on p/p’ GaN layers by silicon ion-implantation. Post-implantation damage removal was performed by annealing the samples at 1260°C in N2/NH3 ambient. In devices with a vertical n-p junction topology, light emission under forward bias conditions was observed near the periphery of the n-contact region confirming existence of a n-p junction and indicating that carrier transport across the junction occurs predominantly in the vicinity of the device periphery. Thus, the rectifying behaviour observed in current-voltage measurements is associated with the n-p junctions formed by ion-implantation. The electrical-characteristics of the n-p diodes does not seem to be limited by the quality of the implanted junction but rather by the high spreading resistance of the underlying p-contact layer. The role of this layer was to facilitate contact to the buried n-p junction, however, further optimisation is obviously necessary in order to decrease the sheet resistance.

Improvement of GaN-Based LED with SiO2 Photonic Crystal on an ITO Film by Holographic Lithography: Hsi-Hsuan Yen; Hao-Chung Kuo; National Chiao Tung University

GaN-based light-emitting diode (LED) with SiO2 photonic crystal (PhC) made by holographic lithography on an indium-tin-oxide (ITO) film was fabricated. The PhC made on SiO2, but an ITO film improves the light extraction efficiency of the GaN-based LED and prevents from increasing the resistance of the ITO film. Fig. 1 shows the schematic diagram of the GaN-based LED structure with SiO2 PhC on an ITO film and Fig. 2 shows the SEM photograph of the SiO2 PhC. It was found that the forward voltage at 20 mA of the GaN-based LED with SiO2 PhC on an ITO film was 1.9% higher than the GaN-based LED with an ITO film only. In Fig. 3, it was found that the output power of GaN-based LED with SiO2 PhC on an ITO films was 26.5% and 125.3% higher than GaN-based LED with an ITO or Ni/Au film only, respectively.

Improvement of Light Extraction Efficiency in GaN-Based LED by Patterning p-GaN Using Silica Colloid Mask: Jeong Woo Park; Jeong-Ho Park; Hye-Yeong Koo; Ja-Young Kim; Dong-Yu Kim; Ho-Young Song; Je Won Kim; Yun-Chun Kim; Gwangju Institute of Science and Technology; Samsung Electro-Mechanics Company, Ltd.

Two-dimensional silica colloidal mask was used to etch p-GaN surface to improve the light extraction efficiency of GaN LEDs by randomly patterning p-GaN surface. By treating the p-GaN surface with polyelectrolyte, mono layer silica colloids with 500nm in diameter could be uniformly distributed on the 2-inch p-GaN wafer. The patterns were produced on the p-GaN by using a plasma etching process with Ar:C12:He plasma source gases. LED samples with etching depth of 150nm and 230nm were fabricated on p-GaN and output power was measured with chip-probing. The increase of optical output power of 3% and 7% was observed for etching depth of 150nm and 230nm, respectively compared to a reference sample without patterns on p-GaN surface. These results show that the two-dimensional silica colloidal template can be used to provide random patterns on p-GaN for high-efficiency GaN-based LEDs.
InGaN-Based LED with Low Efficiency Droop at High Operation Current Density: Yun-Li Li; Yi-Ru Huang; ② National Taiwan University

For last few years, there have been a lot of progresses on nitride based light-emitting diode (LEDs), especially InGaN/GaN LEDs with multiple-quantum-well (MQW) structures as active region emitting visible spectrum. However, for InGaN/GaN LEDs, there is a very well-known fundamental problem of efficiency “droop” - the reduction in an LED’s efficiency as its drive current is increased. In this research, InGaN-based blue light-emitting diodes (LEDs) with different multiple quantum well (MQW) structures and growth conditions on c-plane sapphire substrates are investigated. It is observed that the droop effect can be drastically reduced with design of MQW structures, especially the width of wells and barriers of MQWs. For example, performance of external quantum efficiency (EQE) of LEDs is improved at high current densities with thicker wells for MQW structure. Results of temperature-dependent efficiency experiments and current-voltage (I-V) measurements will be further discussed.

InGaN/GaN Light Emitting Diode with R-Plane Polygonal Facet Deflectors: Hyungu Kim; Min Gyu Na; Hyun Kyu Kim; Hee Yun Kim; Jae Hyoung Ryu; Tran Viet Cuong; Chang-Hee Hong; ① Chonbuk National University

A new concept of InGaN/GaN light emitting diodes embedded periodic deflector structure (PDE-LED) were proposed and grown on sapphire substrate with SiO2 hexagonal patterned mask by using selective metal-organic chemical deposition. The artificial polygonal pyramids (AIPPs) were formed on masked areas and showed the [1-102] R-plane polygonal facet of 57° against [0001] c-axis, which can be used as deflector. The designed more than two hundred AIPPs are periodically distributed and revealed the superior capability for enhancing the light extraction efficiency. It is because the AIPP deflector structure can provide photons multiple chances to escape from the LED side wall, contrary to rectangular conventional LED, which is confirmed by electro-luminescence optical microscope photograph inside AIPP over the [0001] surface area.

Integration of a Matrix Addressable Blue/Green LED Array with Multicore Imaging Fiber for Spatio-temporal Excitation in Endoscopic Biomedical Applications: Heng Xu; Kristina Davitt; Yoon-Kyu Song; ② Weidong; Carlos Aizenmann; ③ Art0 Nurmikko; ④ Brown University

We have developed a micro-scale endoscopic optical image projection device, integrating an InGaN MQW two-dimensional (2D)-LED array to a microscopic imaging fiber. A scalable matrix addressing scheme was used for the electrical access to individual elements in the densely packed 2D-LED array. A prototype 10×10 element array was fabricated by specialized device process flow, using deep reactive ion etching and polyimide etch-back processes for device isolation and planarization. Individual elements of the array have been operated under cw current injection up to a few kA/cm², suggesting uncompromised performance and robustness of the device. The array was butt-coupled to a 30,000-pixel multicore image fiber to generate a spatio-temporal pattern of light at the output end of the fiber. As application demonstration, selected illumination patterns have been projected to the retina of Xenopus laevis tadpoles in studies of their developing visual system, as well as optically excitable neural cells in the brain.

Narrow-Band Photodetection Based on M-Plane GaN: Sandip Ghosh; Carlos Rivera; ① Jose Pau; Elias Munoz; Oliver Brandt; ② Holger Grabow; ③ Tata Institute of Fundamental Research; ④ Universidad Politecnica de Madrid; ⑤ Paul Drude Institute for Solid State Electronics

Rapid identification of a range of hazardous airborne biological and chemical agents requires simultaneous detection at several specific wavelengths, and consequently a set of photodetectors with very narrow band spectral responsivity. We demonstrate an ultraviolet photodetector configuration with a detection bandwidth limited to a few nanometers. It consists of a polarization-sensitive planar Schottky photodiode and a filter, both made from a strained M-plane GaN film on LiAlO2(100) substrate, grown using molecular-beam epitaxy. The optical band gap of the film depends on the orientation of the linear polarization of the incident light relative to the c-axis of GaN, which lies in the film plane. An orthogonal alignment of the c-axis of the photodetector and the filter produces a detection system with a peak responsivity at 360 nm and a bandwidth of 6 nm. Electronic-band-structure calculations show that the anisotropic in-plane strain is the crucial parameter for high responsivity and polarization contrast.

Ohmic Formation Mechanism of Ag(Cu) Alloy Contact on p-Type GaN: Jun Ho Son; Gwan Ho Jung; Yun Goo Kim; Changyeon Kim; Yeo Jin Yoon; Jing-Lam Lee; ① POSTECH; ② Seoul Optodevice Co., Ltd.

Ag-based reflective ohmic contacts are widely used due to its high reflectance (>95%) and low contact resistivity. However, annealing in oxygen ambient causes Ag to be oxidized and/or agglomerated, leading to degradation in both electrical and optical properties. In this work, we present the ohmic formation mechanism of Ag(Cu) alloy contacts on p-type GaN. After annealing at 400°C for 1min in air ambient, Ag(Cu) contact showed minimum contact resistivity of ~10-5Ωcm². However, Ag contact showed minimum contact resistivity of ~10-5Ωcm² at 300°C. SRPES results showed that the increase of metallic Ga bonds was significant in Ag(Cu) contact, resulting in lower contact resistivity than Ag contact. HRXRD revealed that Cu atoms disturb the migration of Ag atoms, preventing Ag agglomeration. Additionally, Ag(Cu) contact show good surface morphology than Ag contact. Thus, agglomeration suppression effect caused by the addition of Cu results in the good contact resistivity and smooth surface morphology.

Optical and Magnetic Properties of Fe-Doped GaN Magnetic Semiconductors Prepared by MOCVD Method: Xia Xiangjian; ① Tao Zhikuo; ② Xie Zili; ③ Han Ping; ④ Zhang Rong; ⑤ Nanjing University

Fe-doped GaN thin films have been grown on c-sapphire by metal organic chemical vapor deposition. Crystalline quality and phase purity were confirmed by X-ray diffraction and Raman scattering measurements. No detectable second phases were formed during the growth. Fe-related optical transitions were observed in photoluminescence spectra. Magnetic measurements revealed the films are ferromagnetic with Curie temperature Tc above room temperature. The ferromagnetism may come from carrier-mediated Fe-doped GaN diluted magnetic semiconductors or tiny iron clusters and Fe-N compounds which we have not detected.

Optical Properties of InGaN/GaN MQW Microdisk Arrays on GaN/Si(111) Template: Kang Jea Lee; ① Tae Su Oh; ② Eun-Kyung Suh; ③ Kee Young Lim; ④ Chonbuk National University

Specifically, total internal reflection gives rise to low loss whispering gallery modes (WGM), which propagate along the periphery of disk. Small volumes and high Q-factors of WGMs result in enhancement of optical resonance. It has been expected that GaN microdisk on Si structure can confine light strongly in microdisk cavity, because of the large discontinuity in refractive index at boundary between the cavity and surrounding air. In this work, we report the fabrication of InGaN/GaN MQW microdisk arrays on Si(111) substrates. InGaN/GaN MQWs were grown on GaN on Si(111) templates by MOCVD. The ~50 nm diameter microdisk resonators were fabricated using a combination of optical lithography and a dry etching process by ICP etcher and Si undercut etching by acid chemical solution. The evidence of WGMs in optically pumped microdisk cavities, which some interesting features such as kink spectra, have been observed at room temperature photoluminescence.

Performance of AlInGaN 310 nm LEDs over Laterally Overgrown AlN: Jianping Zhang; Rakesh Jain; Xuhong Hu; Yurii Bilenko; ① I. Shtrum; ② A. Lunev; ③ M. Shatalov; ④ J. Yang; ⑤ R. Gaska; ⑥ Sensor Electronic Technology

We report on AlInGaN 310 nm light emitting diodes (LEDs) deposited on epitaxial laterally overgrown AlN templates. High quality fully coalesced 16 μm thick AlN template layers were overgrown over grooved AlN deposited on c-plane sapphire substrates using combination of MOCVD and Migration Enhanced MOCVD techniques. Standard lateral geometry LED devices were fabricated and flip-chip packaged onto TO-39 headers. CW output power of devices was 0.6 mW at 20 mA which is comparable to our standard 310 nm LEDs on sapphire. Initial 150 hour lifetime testing on-wafer and fully packaged devices showed that LEDs on overgrown AlN were significantly more stable then standard devices on sapphire. Additional peak at 340-350 nm LEDs on sapphire. Initial 150 hour lifetime testing on-wafer and fully packaged devices showed that LEDs on overgrown AlN were significantly more stable then standard devices on sapphire. Additional peak at 340-350 nm LEDs on sapphire. Initial 150 hour lifetime testing on-wafer and fully packaged devices showed that LEDs on overgrown AlN were significantly more stable then standard devices on sapphire.
Technical Program

Photoluminescence Characteristics of GaAsSbN/GaAs (N: 0-2.5%) Single Quantum Well Structures and Light Emitting Diode: Kalyan Nuna1; S. Iyer2; Jia Li3; W. Collins4; 1North Carolina AD&T State University

In this work, we present a systematic study on the variation of structural and optical properties of GaAsSbN/GaAs single quantum wells (SQWs) as a function of nitrogen concentration. These SQW layers were grown by solid source molecular beam epitaxial (MBE) technique and were in situ annealed in As ambient. A high photoluminescence (PL) peak energy reduction of 325 meV (N~1.4%) in the GaAsSbN SQWs was observed with respect to the reference GaAsSb QW. The temperature dependence of the PL in these SQWs exhibited S-curve behavior, a signature of localized excitons. The less pronounced S-curve in temperature dependence, smaller blue-shift in excitation dependence and more symmetric line-shape with increasing N indicate the good quality of the layers. In-situ annealing in the As ambient yielded layers of better quality even at higher N concentrations, contrary to the commonly observed behavior in the dilute nitrides. Light emitting diodes of GaAsSbN/GaAs SQW exhibited a room temperature electroluminescence (EL) peak at 1.61 μm with an output power of 1 mW for 30 mA forward current. The diode exhibited a low turn-on voltage of ~500 mV with an abrupt reverse break-down voltage of 7.5 V. Detailed study of I-V characteristics, output power and EL spectra and its temperature dependence as a function of the forward current will be presented.

Quaternary InAlGaN Quantum-Dot UV-LED Emitting at 335nm Fabricated by Anti-Surfactant Method: Hideki Hirayama1; Sachie Fujikawa2; RIKEN

We succeeded in the fabrication of quaternary InAlGaN quantum dots (QDs) by using anti-surfactant method and demonstrated 335nm current injection emission of the quaternary InAlGaN-QD ultraviolet (UV) light-emitting diodes (LEDs). The InAlGaN-QD UV-LED was fabricated on high-quality AlN/InGaN buffer template directory grown on sapphire substrate by low-pressure metal-organic chemical-vapor deposition (MOCVD). Quaternary InAlGaN-QDs were formed on the InAlGaN buffer surface treated by silicon anti-surfactant. Self-assemble InAlGaN QDs with the lateral size of 10-20 nm and the height of 5-8 nm were successfully grown on InAlGaN surfaces observed from the AFM images. We observed intense photoluminescence (PL) from the InAlGaN QDs with the wavelength at around 335 nm at room temperature (RT). We obtained current injection emission from the InAlGaN-QDs (335 nm) of the InAlGaN-QD UV-LED under RT CW operation. The output power would be much improved with the increase of QD density and the increase of electron injection efficiency.

Radiative Dipole Orientation in InGaN Grown on GaN(0001): Gerd Mueller1; Nathan Gardner2; Anneli Munkholmen3; Michael Krames4; 1Philips Lumileds Lighting

The distribution of radiative dipoles in active layers of c-plane grown InGaN/GaN light emitting devices (LED) strongly influences light extraction, which in turn controls the overall efficiency. The polarization of light emission from the active layer was measured in a suitable geometry using imaging polarization spectroscopy for a large variety of samples ranging from multiple quantum wells, electrically driven, to thick photo-excited pseudomorphic InGaN layers. By carefully avoiding scattered depolarized light, consistently high degrees of polarization were observed, indicating light emission from in-plane dipoles only. The generality of the finding can be explained by assuming that the near gap band structure of InGaN pseudomorphic to GaN(0001) does not allow for appreciable oscillator strength of perpendicular dipoles. As a consequence the extraction efficiency through the (0001) surface is a factor of 1.5x higher than often assumed (i.e., case of isotropic emission).

Stimulated Emission from Ultra-Thin In-Rich InGaN/GaN Multiple Quantum Wells Grown by Metallic Organic Vapor Deposition: Hee Jin Kim1; Ho-Sang Kwack2; Sung-Hyun Park2; Suk Choi3; Keon-Hun Lee3; Yong-Hoon Cho5; Euijoon Yoon5; 1Seoul National University; 2Chungbuk National University

We present the results of a systematic photoluminescence (PL) study of ultra-thin In-rich InGaN/GaN multiple quantum well (MQW). 10 K PL spectra were measured for a very broad range of optical excitation power from 0.1 mW up to 1 kW. Spontaneous emission at 390 nm did not shift with increasing pumping power over 7 order magnitude, indicating that there is negligible quantum confined Stark effect in ultra-thin In-rich InGaN/GaN MQW despite containing 70% indium in InGaN well. To examine the relevance of In-rich InGaN/GaN MQWs to laser applications, optically pumped stimulated emission (SE) experiments were performed at room temperature (RT) in edge emission geometry. When the pumping power density exceeds 1 MW/cm², RT SE from the In-rich InGaN/GaN MQWs was observed at 386 nm at the high energy side of spontaneous emission at 390 nm.

The Effect of Sb Surfactant on the Properties of p-Type GaN: Min-Ki Kwon1; Ja-Seung Jin2; Sung-Hyun Park3; Sunwoon Kim4; Je Won Kim5; Yon-Chun Kim6; Seong-Ju Park7; 1Gwangju Institute of Science and Technology; 2Samsung Electro-Mechanics Company

The effect of Sb surfactant on the properties of p-GaN layer is reported. It was found that the hole concentration was increased and the sheet resistance of Mg-doped p-GaN layer with was decreased with increasing the Sb surfactant. High resolution X-ray rocking curves showed that the structural quality was improved and atomic force microscopy images showed that the surface roughness of the p-GaN layer was decreased with increasing Sb surfactant. In addition, the photoluminescence (PL) peak around 450 nm related to the complex of deep donor (VN) and acceptor (MgGa) was reduced by doping Sb surfactant. The improvement of hole concentration in p-GaN layer could be attributed to the improvement of structural quality and the suppression of formation of VN-MgGa by Sb surfactant during the growth of Mg-doped p-GaN.

Via-Hole-Based Vertical GaN Light Emitting Diode: Hyun Min Jung1; Gi Yeon Nam2; Byung Kyu Choi3; Tae Hee Lee4; Hyun Suk Kim4; Soo Keun Jeon5; Eun Hyun Park7; Chang Tae Kim6; Doo Jin Bak5; 1Epivalley

Recently, III-nitrides have promoted great advances in LEDs. High efficiency GaN-based LEDs attract great interest for applications such as displays, signals, backlight for Liquid Crystal Display (LCD) and white-light sources. Though many approaches have been carried out to increase the external efficiency, the total light output from these LEDs is still rather low. In this study, we found that a vertical GaN-LED has been fabricated on a sapphire substrate with periodic via-holes formed by a laser drilling technique. N-contact metal which was deposited on the backside of sapphire substrate was directly connected with an ohmic metal of n-GaN layer through the via-holes. The via-hole-based vertical GaN-LED demonstrated an optical power improvement up to 12.5% with lower forward operating voltage compared with a conventional GaN-LED. In addition, this vertical LED showed just 0.8% and 1.5% variation of optical power and operation voltage at the 500 hour reliability test.

245-250nm AlGaN-Based Deep Ultraviolet Light-Emitting Diodes Fabricated on High-Quality AlN Buffer on Sapphire: Hideki Hirayama1; Tomoaki Ohashi1; Tohru Yatake2; Norihiko Kamata3; 1RIKEN; 2Saitama University

We demonstrated 245-250 nm AlGaN multi-quantum well (MQW) deep ultraviolet (UV) light-emitting diodes (LEDs) on sapphire substrates. High-quality AlN templates were used that was fabricated by using NH3 pulse-flow technique. N-contact metal which was deposited on the backside of sapphire substrate was directly connected with an ohmic metal of n-GaN layer through the via-holes. The via-hole-based vertical GaN-LED demonstrated an optical power improvement up to 12.5% with lower forward operating voltage compared with a conventional GaN-LED. In addition, this vertical LED showed just 0.8% and 1.5% variation of optical power and operation voltage at the 500 hour reliability test.

LED

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A Novel Technique for Schottky Barrier Reduction to p-Type GaN Layers Using Kelvin Probe Force Microscopy: Takashi Hirota;1 Tatashi Shimamura;2 Chie Hongo;2 Masaaki Onomura;2 Toshiba Corporation, Corporate Manufacturing Engineering Center; 2Toshiba Corporation, Semiconductor Company

Reduction of contact resistance to p-type GaN layers is important for high-reliability InGaN/GaN/GaN-based optical devices. It is effective to reduce Schottky barrier height for improving contact resistance and operation voltage. In this paper, we demonstrate the linear correlation between the surface potential difference at p-type GaN contacts and the work function of metals, using Kelvin probe force microscopy (KFM). KFM is a kind of scanning probe microscopy, and can measure the surface potential directly by a non-contact probe in the air. The surface potential difference, corresponding to Schottky barrier height, was estimated by scanning across p-type GaN surface and metal surface. We evaluated several samples of metal (Pd, Ni, Ti or Pt) formed partially on low resistance p-type GaN layers grown by low-pressure metal organic chemical vapor deposition. The mechanism of Schottky barrier height reduction and low resistance p-type electrodes will also be discussed.

A Novel Chip on Board LED Package Module for LCD Backlight in Car Navigation System. Normally, Car-Navigation System has faceted of selectively grown GaN stripes with an on-wafer optical output power between 1.5 and 2.5 mW at 450 nm. But conventional type LED BLU requires more high cost and show low performance in high temperature. So, LED BLU is one of the alternatives of CCFL BLU. However, some problems have been pointed out. Therefore, in this paper, we report the novel hybrid chip on board (COB) LED package module. The enhanced COB module could be reduced up to 13.9 degree at 30mA compared to conventional type. As the result, COB module sample has shown the stable light-output performance after the time degradation test of 30 minutes.
Carrier Dynamics of InGaN/GaN Light-Emitting Diodes with Various Doping Profiles: \textit{Yun-Li Li}; Yi-Ru Huang; Yun-Chong Chang; \textit{National Taiwan University}; \textit{National Cheng-Kung University}

For last few years, there have been a lot of process growth on nitride based light-emitting diodes (LEDs), especially InGaN/GaN LEDs with multiple-quantum-well (MQW) structures as active region emitting visible spectrum. In this work, active region of InGaN/GaN based LEDs with various doping profiles are investigated. Barriers of MQW structures undoped or partially doped with Si are manufactured with metal-organic chemical vapor deposition (MOCVD). Photoluminescence (PL) and time-resolved photoluminescence (TRPL) experiments on these structures reveal very interesting carrier transport mechanisms with different doping profiles. For the measured samples, carrier lifetimes are reduced with increase of doping layers. This can be attributed to the stronger non-radiative recombination near the heavily doped barrier layers. At the same time, PL excitation intensity-varied experiments demonstrate reduced carrier life time with lower PL excitation intensity for partially doped samples. Measurement results will be further discussed.

Characterization of Plasma Damage-Free InGaN/GaN LED with Periodic Deflectors: \textit{Tran Cuong}; Hyung Kim; Min Na; Hyun Kim; Hee Kim; Jae Ryu; Chang Hong; \textit{Semiconductor Physics Research Center}

Electrical performances of conventional InGaN/GaN LED devices are often limited by the fundamental problem of plasma damage during inductively coupled plasma process. For instance, the degradation of sidewall contamination along with rough surface morphology of n-GaN, increasing the surface recombination of the injected electron and holes might lead to deterioration of the forward and reverse voltage. Thus, in this study, a mesa-shaped LED structure was grown on n-GaN with SiO2 mask pattern by using selective MOCVD to eliminate dry etching process. Use of SiO2 dot pattern inside LED structure can be partially contributed to a flat surface without any edge growth effect, which usually occurred at window edge regions after selective MOCVD growth. Moreover, selective growth on SiO2 dot patterning gives inverted polygonal pyramid structures, which were responsible for the guided light deflector. Consequently, the light output intensity was increased about 20% higher than that of conventional-LEDs, while the electrical performance was compatible with those of conventional-LEDs.

Comparative Study of Temperature-Dependent Electroluminescence Efficiency in Blue and Green InGaN Multiple-Quantum-Well Diodes: \textit{Kenzo Fujitawa}; Hirohiko Inada; Masaji Horiguchi; Akihiko Satake; \textit{Kyushu Institute of Technology}

Origins of the high radiative recombination efficiency in InGaN quantum well light-emitting diodes (LEDs) under influences of high-density misfit dislocations have been receiving much attention. In this paper, the electroluminescence (EL) spectral intensity is comparatively investigated in the c-plane blue and green multiple-quantum-well (MQW) LEDs, fabricated by Nichia, over a wide temperature range (T=20-300 K) and as a function of injection current (I=0.01-10 mA). One striking result of the external quantum efficiency is that its variation pattern with temperature for a fixed current strongly depends on the In content in the active layers. The value is very sensitive to temperature and current level for the blue LED, while less sensitive for the green one. This difference observed between the blue and green MQW-LEDs indicates that the anomalous T dependence of the EL efficiency is caused by interplay of the carrier capture/escape and the internal quantum efficiency.

Comparison of III-Nitride Interband and Intraband Photodetectors Optimized for a Wavelength of 633nm: \textit{Sindy Haaugoth}; Vadim Lebedev; Oliver Ambacher; \textit{Technical University Ilmenau}

Transparent photodetectors for application in high precision standing wave interferometry operating at the wavelength of He-Ne-lasers (633 nm) were investigated in respect to the sensitivity and temporal response. We report on two concepts of photodetectors having a thickness of the active layers of ~20 nm. The first detector concept is based on the intraband transition of GaN quantum well heterostructures. The second one employs thin In-rich InGaN epilayers for photocarrier generation provided by the direct band-to-band transition. The photodetectors based on the interband transitions in InGaN epiarrays showed a >20 times higher absorbance at 633 nm, than those photodetectors based on the intraband transition in the AlIn/GaN/AlGaN heterostructure. However, the temporal response of the latter structure is influenced by the persistence photocurrent adversely affecting performance and operating frequencies.

Effect of AlGaAs Cladding Layer on GaInNAs/GaAs MQW p-i-n Photodetector: \textit{Yung-Feng Chen}; Wei-Cheng Chen; Ricky Chuang; Yan-Kuin Su; Hsio-Li Chai; \textit{National Cheng Kung University}; \textit{Taiwan Semiconductor Manufacturing Company Ltd.}

Electric properties of GaInNAs/GaAs multiple-quantum-well (MQW) p-i-n photodetector with AlGaAs cladding layer has been studied. By applying a higher band gap AlxGa1-xAs to the photodetector, a substantial reduction in dark current was observed owing to an inherent difficulty for holes to surmount the high potential barrier between MQW and cladding layer heterojunctions under a reversed bias. Dark current obtained was as low as 4.1 pA at -3.5 V for a device with AlxGa1-xAs cladding layer. Photodark current contrast ratio obtained were 4.2×105 and 11 for devices with and without AlxGa1-xAs cladding layer, respectively, at -3.5 V. In addition, peak responsivity of 18 mA was measured at around 1150 nm and two orders of magnitude increase in the rejection ratio was also realized at 2.0 V. We intent to demonstrate the GaInNAs/GaAs MQW p-i-n photodetector with AlGaAs cladding layer potentially could provide high photo/dark current contrast ratio and responsivity rejection ratio.

Effects of Sapphire Substrate Misorientation on the GaN-Based Light Emitting Diodes Grown by Metalorganic Vapor Phase Epitaxy: \textit{Akiko Nakamura}; Naoto Yamaiga; Toru Murata; Katsuyuki Hoshino; Kazuyuki Tadatomo; \textit{Yamaguchi University}

We have systematically investigated the influence of substrate substrate misorientation on the structural and optical properties of GaN-based LEDs grown by MOVPE. The LED properties were found to be very sensitive to the misorientation. We grew five samples of LEDs on sapphire substrates with various misorientation angles (θ= 0.02–1.0°). The EL intensity increased when θ increased to 0.25°. The intensity, however, decreased dramatically when θ exceeded 0.25°. We also grew the samples of each layer of the LED, viz., GaN, InGaN, InGaN/GaN MQWs, and p-GaN layer. CL and PL analyses showed that the crystalline quality of InGaN (MQWs) layer became lower while that of GaN layer improved as θ increased. In addition, the increased misorientation caused the decreased Indium composition and the Indium compositional fluctuation. Moreover, the hole concentration of p-GaN layer decreased with increasing θ. As these results, the misorientation angle of around 0.25° is suitable for the LEDs.

Effects of the p-Electrode Reflectivity on the Extraction Efficiency of Nitride-Based Light Emitting Diodes: \textit{Jaehyong Choi}; Hyunsoo Kim; Yongjo Park; Euijuo Yoon; \textit{Seoul National University}; \textit{Samsung Advanced Institute of Technology}

For the realization of solid-state lighting using nitride-based light emitting diodes (LEDs), the achievement of high extraction efficiency of LEDs is crucial. However, it is well known that only a small fraction of photons generated in a GaN LED can escape due to the total internal reflection at the interface between GaN and outer medium. To overcome the intrinsic limitations of the GaN LED structures and to extract more light out from the LED surface, use of high reflectivity electrode is inevitable. First, the dependency of the extraction efficiency on the p-electrode reflectivity is simulated by a point-and-shoot ray tracing method. Secondly, a few p-contact
Enhanced Light Extraction from GaN-Based Green Light-Emitting Diode with Photonic Crystal: Ja-Yeon Kim; Min-Ki Kwon; Il-Kyu Park; Sang Hoon Kim; Ki-Dong Lee; Seong-Ju Park; ’Gwangju Institute of Science and Technology; ’LG Electronics Institute of Technology

Recently, the effect of two-dimensional (2D) photonic crystal (PC) has been investigated to enhance the light extraction efficiency of light-emitting diodes (LEDs). However, the effect of PC structures inside and outside photonic bandgap (PBG) on the performance of GaN-based LED has not yet been reported. We report on the GaN-based green LEDs with PC structure inside PBG (PCIG) and outside PBG (PCOG). With decreasing the distance from photoluminescence (PL) detection angle from 140° to 60°, the enhancement of PL intensity of LED with PCIG was largely increased from 9-fold to 25-fold compared to that of LED without patterned structure, while the PL intensity of LED with PCOG was increased from 4.6 to 5.6-fold. The optical output power of green LED with PCIG was enhanced by about 2-fold compared to that of green LED with PCOG. These results suggest that the light extraction of green LED can be greatly increased by using PCIG.

Enhanced Light Extraction from Triangular GaN-Based Light-Emitting Diodes: Ja-Yeon Kim; Min-Ki Kwon; Jae-Pil Kim; Seong-Ju Park; ’Gwangju Institute of Science and Technology; ’Korea Photonics Technology Institute

The improvement in light extraction efficiency of GaN based LED is considered to be crucial, and several methods have been proposed to enhance the light extraction of LEDs. However, all these studies were performed on a quadrangular (QDA) LED and other than the QDA LED have not been reported. In this study, the properties of a triangular (TRA) LED are compared with those of a conventional QDA LED. The total radiant flux from the packaged TRA LED, which was grown on patterned Sapphire substrate, increased by 48% and 24% at input currents of 20 and 100 mA, respectively, compared to that of a QDA LED. In light far-field beam distribution, the light extraction in the horizontal direction of the LED was much higher than that of the QDA LED due to the enhancement of light emission from the side walls of the TRA LED.

Enhanced Output of GaN-Based UV light-Emitting Diode with TiO2/Al2O3 Distributed Bragg Reflector: Tak Jeong; ’Korea Photonics Technology Institute

An high reflectivity distributed Bragg reflector (DBR) for ultraviolet spectrum is realized by TiO2/Al2O3 multilayer stack. The 4 pair TiO2/Al2O3 DBR has much higher reflectivity than Ag-based omnidirectional reflector (ODR) at a wavelength of 380nm. The electric and optical properties of the DBR-LED are comparable to those LED with ITO/Ag ODR. It is experimentally shown that GaN-based UV LED with TiO2/Al2O3 DBR showed good I-V characteristic and an enhanced optical power compared to that with Ag-based ODR due to the high reflectivity(85% at 380nm).

Enhancement of Light Extraction Efficiency in InGaN Based LED Using Patterned n-GaN Substrate: Si-Hyun Park; Kwang-Woo Kwon; June Key Lee; Sang Wan Ryu; ’Chosun University; ’NIXEN Company, Ltd.; ’Chonnam National University

Light extraction efficiency from InGaN-based light-emitting diodes was improved (LEDs) where we patterned n-type GaN layer onto a Sapphire substrate with a nano-sized SiO2 columns. We performed the deposition of an indium tin oxide thin layer on SiO2 layer and then wet etching, which gave rise to an oxide self-assembled clusters of a few-hundred-nm size. A subsequent SiO2 etching with the oxide mask results in a SiO2 columns on n-type GaN Layer. We showed the output power of the patterned n-GaN substrate (PNS) LED was increased a 1.33 time compared to that of the normal LED without n-GaN pattern when a total output power emitted in all direction from the packaging LED was measured under a current injection of 20 mA. The increase of output power from PNS-LED depends on the SiO2 column size onto n-type GaN substrate.

EpiEL Provides Advanced Optical Characterization for Nitride LED Epi-Wafers: Max Xianyun Ma; ’MaxMile Technologies, LLC

A virtual LED device fabrication and characterization technology, called EpiEL, has been developed to nondestructively measure LED device parameters directly on epiwafers. For nitride LED epiwafers, without any costly and time-consuming device fabrication, EpiEL can be used to not only rapidly map electro-luminescence (EL) and electrical properties of the material, but also simulate different light extraction approaches. Recent investigation indicated that most of current nitride-based LED epiwafers have a non-uniform material structure which leads to different optical observations at epitaxial and substrate sides. A possible material structure deficiency will be discussed during the presentation.

Estimation of Internal Quantum Efficiency in InGaN-Based Light Emitting Diodes Using Electroluminescence Decay Times: Shinji Saito; Tetsuo Narita; Kotaro Zaima; Koichi Tachibana; Hajime Nago; Gen-ichi Hatakoshi; Shinya Nunoe; ’Toshiba Corporation; ’Nagoya University

InGaN-based Light Emitting Diodes (LEDs) have been extensively developed for fabrication of efficient solid-state lighting. Performance of LEDs is defined as the external quantum efficiency, which is the product of injection efficiency, internal quantum efficiency (IQE), and the extraction efficiency. Although the IQE could be analytically determined, few works were reported on the determination method. We investigate the IQE of InGaN-based LEDs from the semiconductor rate equation of pulse current injection. A method is presented for the IQE based on data of electroluminescence decay times measured as a function of current in the pulse injection. For the screening of built-in electric field, the pulse current was injection with bias voltage. For blue LED, the IQE was measured to be about 70%. It is found that the IQE increase with injection current, whereas the external quantum efficiency decreases at high injection.

Exciton Localization in InGaN/AlGaN QW and 340 nm Ultraviolet Light Emitting Diodes: Keun Lee; Peter Parbrook; Tao Wang; Jie Bai; Fabio Ranalli; Qi Wang; Rob Airey; Geoff Hill; ’University of Sheffield

The optical properties of InGaN/AlGaN quantum wells (QW) and 340 nm ultraviolet (UV) light emitting diodes (LEDs) have been studied by photoluminescence (PL) and electroluminescence (EL). The temperature dependent luminescence from 10 K to 400 K shows a classical ‘S-shape’ behaviour, attributable to exciton localization from well thickness fluctuations. The localization is found to be excitation intensity/injection current sensitive. As the injection current increases from 5 mA, the value of σ, indicating the degree of localization, gradually decreases from 14 meV until eventually the S-shape behaviour vanishes. We also examine the localization behaviour in both cases using a Gaussian distribution localized-state model proposed by Li et al [APL 79, 1810 (2001)] which in principle allows the emission energy at low temperatures (below 77 K) to be modelled. The role of aluminium composition in localization in the QW for deeper UV LEDs is also discussed.

Fabrication of GaN-Based MOS LEDs for Micro Pixels in Flat-Panel Displays: Tohru Honda; Toshiaki Kobayashi; Shigetoshi Komiyama; Yoshihiro Mashiyama; Masatoshi Arai; Kaori Yoshioka; ’Kogakuen University

Micro-size integrated light-emitting diodes (LEDs) that operate in the UV spectral region were fabricated using GaN layers grown on sapphire substrates by metal-organic vapor phase epitaxy (MOVPE). Schottky-type (ST) and metal-oxide-semiconductor (MOS) LEDs were realized. The near-band-edge emission of GaN was observed in the electroluminescence spectra with reversed bias under pulsed-voltage conditions. The insertion of an aluminium oxide layer in the GaN-based LED leads to an increase in electroluminescent intensity. The pseudo-heterostructure created by the thermal energy also affected the emission pattern. The refractive index in the emission area was increased with the thermal narrowing. A spotty emission pattern was observed. Here, the light was observed from the sapphire substrate side. No light output was observed from some areas such at the edge of the device. This result indicates a reduction of light interference in each device during its electrical operation.
Fabrication of GaN-Based UV TF-ELDs by CS-MBE Technique and Their Application to RGB Light-Emitting Pixels: Masatoshi Arai; Koichi Sugimoto; Shinichi Egawa; Tohru Honda; Kagakuen University

Out-door-type large-scale flat-panel displays (FPDs) have been achieved using GaN-based LEDs. However, out-door-type small-scale (personal-use) FPDs require the development of cost-effective light-emitters for their pixels. UV GaN-based thin-film electroluminescent devices (TF-ELDs) operating were fabricated on Al substrates, whose GaN films were deposited by compound-source MBE technique. The pixels were fabricated using the GaN-based TF-ELDs combined with RGB phosphors. In this paper, the emission efficiencies of RGB phosphors in the time of the excitation by the UV TF-ELDs are discussed. Excitation efficiency was estimated by the PLE measurement of the RGB phosphors. The estimated excitation efficiency of the RGB phosphors at 370 nm were 8.3, 6.0 and 2.5%, respectively. The estimated luminance of each emitter is resulted in 3.2, 7.9 and 10.9 cd/m², respectively. The estimated luminance of the RGB light-emitting pixel is enough to the application for FPDs in comparison with the luminance of typical FPDs.

First All-HVPE Grown InGaN/InGaN MQW LED Structures for 440–510 nm: Alexander Syrkin; Vladimir Ivanov; Oleg Kovalenko; Alexander Usikov; Vladimir Dmitriev; Zuzana Lilienthal-Weber; Meredith Reed; Eric Readinger; Michael Wraback; TDI, Inc.; Lawrence Berkeley National Laboratory; U.S. Army Research Laboratory

Development of alternative epitaxial technology and LED structures is extremely important for solid state lighting (SSL) progress. HVPE is known to produce low defect GaN, AlN, and AlGaN materials, however InGaN HVPE results so far have been limited. In this paper, the first InGaN-based blue (440–490 nm) and green (490–510 nm) LEDs grown by HVPE are reported. The structures are based on InGaN/InGaN multi quantum well (MQW) structures grown by HVPE. Growth InGaN MQWs and superlattices were studied by x-ray diffraction and TEM. Extended defects intersecting InGaN/InGaN structures were not found. These LED structures having “upside down quantum wells” were grown on thick low resistive p-GaN/sapphire templates. Parameters of processed device structures will be presented. Advantages of such device geometry will be discussed. Demonstration of blue and green LEDs by HVPE technology opens a novel avenue for low defect material structures and low cost production technology for SSL application.

Growth and Characterization of a Novel Hyperspectral Photodetector Using the III-Nitrides: Neeraj Tripathi; James R. Grandusky; Vibhu Jindal; Fateneh Hadijedpour-Sandske; Douglas Bell; College of Nanoscale Science and Engineering, University at Albany; California Institute of Technology

We report on the growth and characterization of a novel tunable hyperspectral photodetector using the III-nitrides. The proposed structure consists of a stepped triangular barrier of Al(x)Ga(1-x)N multilayer with Al composition between 0% and 100% grown on a GaN/sapphire template. The Al(x)Ga(1-x)N heterostructure forms a triangular potential barrier whereby the height can be tuned by varying the applied voltage. Internal photoemission (IPE) measurements have been carried out to measure the potential barrier faced by the photocreated excitors. A reduction in potential barrier by 0.65 eV is observed over an applied voltage of 1.3 V, confirming the tunability of detection wavelength. Current-voltage measurements and atomic force microscopy have been used to study the device structure and improve the performance. IPE, I-V and AFM results will be presented along with the principle of device operation, tunability range and device structure optimization parameters.

High-Speed Al(Ga)N/GaN-Based Intersubband Photodetectors at Telecommunication Wavelengths: Eva Monro; Fabien Guillot; Esther Baumann; Fabrizio Giorgetta; Daniel Hofstetter; Laurent Nevou; Maria Tchernycheva; Francois Julien; Thilo Remmele; Martin Albrecht; CEA-Grenoble; Université de Neuchâtel; Université Paris-Sud; Institut für Kristallzüchtung

Thanks to their large conduction band offset (~1.8 eV for the GaN/AIN system) and subpicosecond intersubband (ISB) scattering rates, III-nitride nanostructures are excellent candidates for ultra-high-speed unipolar devices operating at optical-fiber telecommunication wavelengths. In this work, we report the MBE growth, fabrication and characterization of Al(Ga)N/GaN-based ISB detectors for telecommunication wavelengths, around 1.55 μm. The active region of these devices consists of Si-doped short-period GaN/Al(Ga)N superlattices. Quantum well infrared photodetectors fabricated on these samples display a spectrally-narrow photovoltaic response to TM-polarized light around 1.55 μm at room temperature, and can be operated at frequencies up to 2.3 GHz. We have investigated the effect of the growth temperature, Si doping, barrier thickness, Al mole fraction in the barriers and number of periods on the structural and optical properties of the superlattices, and on the performance of the final devices. Results are interpreted in comparison with self-consistent simulations of the electronic structure.

High Brightness Near-Ultraviolet Resonant Light Emitting Diodes: Brian Corbett; Diane Zhu; Brendan Roycroft; Pleun Maaskant; Mahbuk Akhter; Clifford McAleese; Menno Kappers; Colin Humphreys; Tjyndall National Institute; University of Cambridge

Planar near-ultraviolet 385 nm emitting resonant LEDs containing three quantum wells have been investigated as a function of the separation between the wells and a reflective and injecting metal mirror. The extracted output power and far field of the LEDs depend on the precise positions of the wells with each well having a significant individual influence on these properties. A doubling of the output power is obtained when the wells are located around the antinode position of the standing wave while narrower far-fields are obtained with other placement of the wells. A power of 0.4 mW into a numerical aperture of 0.5 is obtained for a current of 30 mA. Calibration of the growth rate along with accurate knowledge of the material properties of the semiconductor and metal mirrors is required for controlled and enhanced emission from planar UV LEDs.

High Performance AlxGa1-xN-Based Avalanche Photodiodes: Turgut Tur; Bilkent University

In this work, we present the MOCVD growth, fabrication, and characterization of AlGaN-based solar-blind APDs. The avalanche gain at 68V was in excess of 1,560 with no Geiger mode breakdown. This work demonstrates the high potential of AlGaN APDs for the replacement of the PMTs for high sensitive solar blind photodetector applications.

High Temperature Degradation of Ohmic Contacts on p-GaN for Application in Light Emitting Diodes: Matteo Meneghetti; Lorenzo Trevisanello; Ulrich Zehnder; Gaudenzio Meneghesso; Enrico Zanoni; University of Padova; OSRAM-OS

This paper analyzes the instabilities of ohmic contacts on p-GaN during thermal stress. The contributions of the ohmic contacts and semiconductor degradation are separated by means of the Transfer Length Method (TLM). Before stress, the I-V curves of the TLMs showed linear shape, indicating good ohmic behaviour of the contacts. Temperature treatment induced the increase of the sheet resistance of the p-GaN and the non-linearity of the characteristics of the contacts. This paper shows that the high temperature instabilities are related to the interaction between device surface and hydrogen in the PECVD-SiN passivation layer implying the decrease of the effective acceptor concentration at TLM surface, and the non-linearity of the contacts and sheet resistance increase. Degradation process was found to be reversible, after passivation removal and subsequent annealing. Finally, a technique for the deposition of passivation layers alternative to PECVD and stable at high temperature levels is proposed and demonstrated.

High Temperature Ohmic Contacts to p-Type GaN Using Boride and Nitride-Based Refractory Materials for Light Emitting Devices: Lars Voss; L. Stafford; M. Hlad; B. Gila; C. Abernathy; S. Pearon; J. Ren; I. Kravchenko; University of Florida

Development of p-type Ohmic contacts for GaN is of interest due to the importance of contact stability and low contact resistance for AlGaN/GaN laser diodes and on light output efficiency from nitride-based light-emitting diodes (LEDs). Commonly used schemes involve high work function metals such as Ni, Pt, or Cr with an overlayer of Au. While these contacts exhibit reasonable contact resistances, their thermal stability is a concern for both device operation at elevated temperatures and during device packaging.
We report on Ohmic contacts to p-GaN using families of boride and nitride based materials. Specific contact resistances in the range of 1×10⁻⁴ for Ni/AlN/X/Ti/Al based contacts and 1×10⁻³ for X/Ti/Al, where X is the high temperature material, are observed over a wide range of anneal temperatures up to 1000°C. LEDs using these materials display much better characteristics after long periods at elevated temperatures than those with just Ni/Al.

**Hybrid Organic/Nitride Micro-Structured Light-Emitting Diodes**: Endan Gu; Benoit Guilhaubert; David Elfrstrom; Zheng Gong; Haoxiang Zhang; Martin Dawson; A. Mackintosh; A.J.C. Kuehne; R.A. Pethrick; C. Belton; D.D.C. Bradley; ‘University of Strathclyde; Imperial College London

Hybrid organic/nitride optoelectronic devices will take full advantage of the optical and electronic properties of both organic and nitride materials. The significant benefits of integrating organic optoelectronic materials such as light-emitting polymers (LEPs) with nitride light-emitting diodes (LEDs) have been identified recently. However, due to their high chemical sensitivity, fabricating polymer microstructures and integrating them with nitride LEDs present a considerable technical challenge. In this work, several approaches for fabricating organic functional polymer microstructures on AlN/GaN-based micro-structured LEDs have been developed, including self-aligned direct writing, ultraviolet laser writing and lithographic patterning. It is shown that the fabricated organic/nitride micro-structured LED devices have well defined microstructures and exhibit novel functionalities. Colour down-converted visible emission from these hybrid electroluminescent micro-structured LEDs has been achieved. These hybrid LEDs offer a promising route to development of a range of low-cost and highly efficient micro-light sources.

**Identification of Mechanisms Responsible for High-Current Efficiency Rollover in III-Nitride Light-Emitting Diodes**: Kirill Bulashevich; Sergey Karpov; ‘Semiconductor Technology Research, Inc.

Most if not all of III-nitride light-emitting diodes (LEDs) suffer from the emission efficiency rollover typically observed at the current densities of ~5-50 A/cm², which limits the high-current device performance. Using simulation, we have examined various mechanisms tentatively responsible for this effect: the electron leakage into the LED p-layers, the carrier delocalization from the In-rich regions formed in InGaN active layers due to compositional fluctuations, the Auger recombination in the active layers, and the LED self-heating. The electron leakage and carrier delocalization can be ruled out, as they become valuable at either much higher or much lower current densities, respectively. The Auger recombination is found to be the most probable non-thermal mechanism producing the efficiency decrease with the current density. The LED self-heating, ever increasing with current, may additionally reduce the efficiency. Possible reasons for importance of the Auger processes in wide-bandgap III-nitride materials are discussed in the paper.

**Improved Light Extraction Efficiency of GaN-Based Light Emitting Diodes by Using Needle-Shape Indium Tin Oxide p-Contact**: Kazuyuki Tadatomo; Fumio Ishida; Kazumasa Yoshimoto; Katsuyuki Hoshino; ‘Yamaguchi University; ‘Yamaguchi Prefectural Industrial Technology Institute

The high-efficiency GaN-based light emitting diodes (LEDs) with improved light extraction efficiency (LEE) using the needle-shape indium tin oxide (ITO) p-contact was successfully demonstrated. The needle-shape ITO p-contact was naturally grown by using electron-beam evaporation method under the precisely controlled condition. The structure of ITO p-contact varied sensitively from the planar-shape to the needle-shape with decreasing the deposition temperature and the partial oxygen pressure in the vacuum chamber. We fabricated the needle-shape ITO p-contact and those with the planar-shape ITO p-contact using the same LED wafer. The external quantum efficiency (EQE) of the needle-shape ITO-LED is 1.5 times larger than that of the planar-shape ITO-LED. This improvement is attributed to the dramatic increasing of the LEE of the needle-shape ITO-LED. These results show that the optimizing shape of ITO p-contact is the key technology to increase the EQE and the LEE of ITO-LED.

**Improvement in Light Extraction Efficiency in GaN Based LED by Nano-Scale p-GaN Roughening**: Jane Lee; ‘Chonnam National University

We improved the light extraction efficiency of 380nm Ultra-Violet Light Emitting Diode (LED) by nano-size roughening of p-GaN surface. The surface roughening process is carried out by using self-assembled gold cluster as a mask. The surface roughness of p-GaN surface is controlled by p-GaN regrowth time on patterned p-GaN layer. At optimized regrowth time of p-GaN layer, that is 30 sec, LED exhibited approximately 60% increased electro-luminescence value compared to the conventional LED. Current-voltage measurement also showed that the electrical properties are considerably enhanced over those of conventional LED chip.

**Improvement of InGaN/GaN Top- Emitting Light-Emitting Diodes Having ZnNi/ITO p-Type Ohmic Contacts**: S.W. Chae; Kyoung Chan Kim; D. H. Kim; S.K. Yoon; B.W. Oh; D.S. Kim; H.K. Kim; Y.M. Sung; T.G. Kim; ‘Korea University; ‘Samsung Electro-Mechanics Company

We report the formation of a high-transparent and low-resistant p-type GaN ohmic contact using a ZnNi/ITO (5nm/380nm) electrode scheme for high-brightness top-emitting light-emitting diodes (LEDs). Along with the ZnNi/ITO electrode, Pt/ITO (5nm/380nm), Ni/Al/ITO (2.5nm/5nm/380nm), and Ni/Al (2.5nm/5nm) electrodes on p-type GaN were prepared to compare their performance. From the measurements, the ZnNi/ITO contacts showed the best performance with a specific contact resistance of ~1.2×10⁻⁴ Ω cm² and a transmittance of ~90% at a wavelength of 460nm. InGaN/GaN multiple-quantum-well LEDs fabricated with the annealed ZnNi/ITO p-type electrodes gave a mean forward-bias voltage of 3.25V and a typical brightness of 11.7 mcd at 20mA. These improvements were attributed to the low light absorption coefficient of ZnNi oxides, as well as to the reduced ionization energy of the Mg acceptor, resulting from hydrogen desorption by ZnNi in the Mg-H complex during thermal annealing.

**Improvement of Near-Ultraviolet Nitride-Based Light-Emitting Diodes with Meshed p-GaN**: H. C. Feng; C. M. Chen; C. W. Kuo; Y. K. Fu; C. J. Tsu; C. J. Pan; G. C. Chi; Cheng-Huang Kuo; ‘National Central University; ‘National Synchrotron Radiation Research Center

This investigation presents nitride-based near ultraviolet (n-UV) light emitting diodes (LEDs) with a meshed p-GaN layer. With 20 mA injection current, it was found that forward voltages were 3.33 and 3.39 V while output powers were 9.0 and 10.6 mW for the meshed indium-tin-oxide (ITO) LED and meshed p-GaN LED, respectively. The larger LED output power is attributed to increased light extraction efficiency.

**Influence of InGaN/GaN Strained Layer Superlattice under Active Layer on the Performance of InGaN/GaN Quantum Well Light-Emitting Diodes**: Shi Jong Leem; Kyoung Chan Kim; Youngboo Moon; Tae Geun Kim; ‘Korea University; ‘Seoul National University

We investigated the performance of InGaN/GaN quantum well light-emitting diodes (LEDs) having InGaN/GaN strained layer superlattice (SLS) as a strain buffer layer for active layers. With increasing indium mole fraction of InGaN/GaN SLS, it was found that the roughness of surface was significantly reduced and the density of V-defects was gradually decreased without changing the size of V-defects. The wavelength shift was as small as 7 nm for the LEDs with In₀.₃Ga₀.₇N/GaN SLS while that for the LEDs with In₀.₃Ga₀.₇N/GaN SLS was as large as 20 nm. The reduction in the wavelength shift in the In₀.₃Ga₀.₇N/GaN SLS LEDs is thought to be due to the low density of V-defects as well as the reduced roughness of surface, resulting from strain relaxation and reduction of the piezoelectric field in MQW as the indium mole fraction of the InGaN/GaN SLS increases from 2 to 10%.

**InGaN/GaN Multiple Quantum Well Blue LEDs Grown on Patterned Si Substrates with High Temperature AlN-AlGaN Stacked Buffer Layers**: Hu Liang; Hui Wang; Yong Wang; ‘Institute of Photonics Technology, Center, Department of Electrical and Computer Engineering, Hong Kong University of Science and Technology

Incorporation of an 500 nm Al₀.₃Ga₀.₇N buffer layer with high-temperature (960°C) AlN interlayers was effective in stress reduction to grow thick crack-free InGaN/GaN blue LEDs on patterned Si substrates with square islands. Compared with previously used AlN interlayer only, the HT AlN-AlGaN...
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stacked buffer layer not only effectively reduced the tensile stress inside devices, but also introduced less threading dislocations. LED device yield was much improved with these AlN/AlGaN composite buffer layers. Previously, micro-cracks easily developed after thermal cycles during device processing and resulted in a very low yield, although as-grown samples were crack-free. Devices with standard Ni/Au surface emitting contacts exhibited ~1.0 mW output power at 20 mA, without Si substrate removal and packaging. With our optimized Ag-ITO contacts, LEDs on sapphire substrates emit 40% more power than Ni/Au contacts, with similar Vth (3.1 – 3.4V). Optimized ITO contacts and substrate transfer are being developed for better device performance.

Junction Temperature Analysis in Green Light Emitting Diode Dies on Sapphire and GaN Substrate: Jayantha Senaviratne; Wei Zhao1; Theeradetch Detchprohm; Yufeng Li; Mingwei Zhu; Yong Xia1; Arya Chatterjee2; Joel Plawsky2; Christian Wetzel2; ‘Future Chips Constellation’. Dies of active size 350x350 μm2 grown on bulk GaN and sapphire substrates of different size at current densities up to 267 A/cm2. Analysis of the experiment was supported by realistic three-dimensional finite-element simulations of the thermal properties. Sapphire based LED dies reach a junction temperature as high as 240 °C at a current density of 133 A/cm2, while those on bulk GaN only heat to 83 °C. By help of this calibration, the role of junction temperature in the spectral light output to thermal resistances of 425 K/W and 63 K/W, respectively. We compare dies of active area 350x350 μm2 on GaN and SBW of the AlN/Al0.1Ga0.9N DBR slightly decrease, compared with the effective lattice-matched AlInN/GaN distributed Bragg reflectors (DBRs) with or without InGaN/GaN quantum wells (QWs) as an active region. Using a micro-transmission setup, it is shown that these QWs exhibit a large in-plane disorder likely resulting from cavity or DBR thickness fluctuations. Although cavity modes with quality factors up to 2800 have been measured in empty QWs, their wavelength varies with position on a short length scale. Extended homogeneous areas separated by abrupt variations are observed. In addition inserting InGaN/GaN QWs brings an extra source of disorder possibly due to their non-uniform thickness. The setup has been subsequently upgraded to allow for angular resolved measurements while keeping a micron scale resolution. This new degree of freedom led to the observation of the cavity mode quantization with angle.

Light Emission Enhancements of InGaN/GaN Single-Quantum-Well Light-Emitting Diodes through Surface Plasmon Coupling: Dong-Ming Yeh1; Chi-Feng Huang1; Tsung-Yi Tang1; Cheng-Yen Chen2; Yen-Cheng Lu1; C. C. Yang3; ‘National Taiwan University’. It has been shown that the coupling of surface plasmon (SP) with an InGaN/GaN quantum well (QW) can enhance photoluminescence (PL). In this paper, we demonstrate the SP-QW coupling effect in an InGaN/GaN single-QW light-emitting diode (LED), i.e. the enhancement of electroluminescence (EL). For the demonstration, we prepare three InGaN/GaN single-QW LEDs of the same structure except that three different metals of Ag, Al, and Au are used as the contacting metals on Ni for the p-type Ohmic contacts. From the different output EL spectra of the three LEDs, one can observe the different SP-QW coupling behaviors. Such different behaviors are confirmed with the results of PL and time-resolved PL measurements. With the InGaN/GaN QW emission around 440 nm in wavelength, the Ag-coated LEDs show the most significant SP-QW coupling effect, as predicted. In this LED sample, the EL spectrum is the strongest, the narrowest and the most blue-shifted.

Light Emitting Diodes with Wavelength-Tunable Output: W.N. Ng1; C.H. Leung2; P.T. Lai2; ‘University of Hong Kong’. It would be very desirable to have LEDs whose wavelengths are tunable by the user over a broad spectral range. Such devices would enable a wider range of LED-based products to be developed, including desktop-sized displays, mood-lighting, etc. We introduce the design and implementation of a broadband tunable LED, with emission wavelength ranging between 470nm and 600nm. This can be achieved through the micro-light-emitting diode strategy, where multiple individually-addressable micrometer-scaled pixels are formed on a 470 nm GaN LED. Red fluorescent microspheres for colour conversion are introduced onto designated pixels, which are interconnected. Pixels in an array emit either blue or red colour. Since the pixels are of micron-scale which are non-resolvable by the unaided human eye, the output appears optically mixed. By varying the intensity of the blue and red emitting regions by varying the bias voltages to the corresponding cathodes, the output wavelength (colour) can be continuously tuned.

Mechanism of GaN/AlGaN UV LED Degradation: Shayla Sawyer1; S. Rumyanstev1; M. Shur2; X. Hu3; A. Sattra2; Yu. Bilenko2; I. Shurni3; A. Lunev4; J. Deng5; J. Zhang2; R. Gaska2; ‘Rensselaer Polytechnic Institute’. We report on studies of degradation of GaN/AlGaN 280nm UV LEDs fabricated by Sensor Electronic Technology, Inc. The estimated lifetime of these tested LEDs is 500 hours, assuming an exponential decrease of the output power with time. During the aging there was no change in peak wavelength, FWHM, series resistance and low frequency noise. At high bias voltage current increased and noise decreased with aging. This experimental data showed that neither series resistance nor the multiple quantum well light emitting structure deteriorate with age. The increase of the current and decrease of the output power can be explained by the lowering of the potential barrier associated with the p contact with aging. These results will help improve the UV LED design and increase their lifetime.

Non-Polar a-Plane AlN/AlGaN Distributed Bragg Reflectors: Tiankai Zhu1; Amélie Dussaigne1; Gabriel Christmann1; Eric Feltin1; Claire Pinquier1; Denis Martin1; Nicolas Grandjean1; ‘Ecole Polytechnique Fédérale de Lausanne’. Highly reflective a-plane AlN/GaN and AlN/AlGaN AlxGa1-xN distributed Bragg reflectors (DBRs) have been achieved for the first time. Samples are grown by ammonia source molecular beam epitaxy on a-plane GaN templates which are previously elaborated by hydride vapor phase epitaxy using epitaxial lateral overgrowth technique. Both DBRs use 13 periods. The room-temperature micro-reflectivity reveals that the AlN/AlGaN DBR is featured by a flat stopband, with a stopband width (SBW) around 35 nm. Its peak reflectivity is roughly estimated around 95%. Both the peak reflectivity and the SBW of the AlN/AlxGa1-xN DBR slightly decrease, compared with the AlN/GaN one. The cross-sections of the DBR structures are characterized by scanning electron microscopy. We demonstrate that the present a-plane DBRs are of comparable optical quality to those grown on c-plane. Thus, they are promising for the fabrication of polarization-free nitride-based microcavities.

Novel Phosphor-Free White Light Emitting Diodes for Optimized Eye Response: Sucheta Ahmed1; David Lancefield1; Stephen Sweeney1; Philippe De Mierry2; Frank Tinjod2; Sébastien Chenot2; ‘University of Surrey’. We report on phosphor-free white GaN homojunction light emitting diode (LED) structures grown both with and without an additional undoped AlGaN barrier. The electroluminescence measured from both devices exhibits yellow defect related emission. However, the incorporation of an AlGaN barrier introduces an additional blue peak relating to the Mg doping profile. This gives rise to broadband “white” emission from the AlGaN barrier devices. Tristimulus values (to analyse the quality of light for human vision) show that in both structures, the red and green responses increase sub-linearly with current. However, the introduction of the AlGaN barrier causes a substantial current induced increase in the blue emission response compared with the
simple homojunction. We find that the AlGaN barrier devices also exhibit a colour rendering index of over 85 and a correlated colour temperature of 6000K. These results illustrate the importance of understanding and controlling defect-related emission for application in broadband LEDs.

**Observation of Phonon-Assisted Stimulated Emission from Pendeo-Epitaxy GaN Stripes Grown on 6H-SiC Substrates: Yun-Chong Chang; Yun-Li Li; Darren B. Thomson; Robert F. Davis; National Cheng Kung University; National Taiwan University; North Carolina State University**

Phonon-assisted stimulated emission (PASE) has been demonstrated by photo-pumping GaN stripes fabricated via pendeo-epitaxy in films grown on 6H-SiC (0001) substrates. Stimulated emission with well-defined Fabry-Pérot modes located at one longitudinal optical (LO) phonon energy (90 meV) below the bandgap of GaN was observed at 77K, and the emission was transversely-electric-polarized (TE). The observed well-defined Fabry-Pérot modes and TE-polarized output verified the occurrence of PASE. An effective refractive index of 8.578 is obtained using a cavity length of 13.3 μm and mode spacing of 0.6 nm. The measured effective refractive index is significantly higher than the 2.8 value obtained from results of spectroscopic-ellipsometry, which indicates higher carrier loss occurs during stimulated emission. Results from this study provide a way to study carrier loss mechanisms during stimulated emission and pave the way for better understanding of the nature of phonon-assisted stimulated emission.

**Optical Characteristics of Two-Dimensional Electron Gas in Undoped AlGaN/GaN Heterostructures with a Low-Temperature AIN Interlayer: Ho-Sang Kwack; Yong-Hwan Kim; Hee Jin Kim; Euijoon Yoon; Yong-Hoon Cho; Chungbuk National University**

We have investigated the optical characteristics of two-dimensional electron gas (2DEG) in Al0.55Ga0.45N/GaN heterostructures with and without a low-temperature AIN interlayer grown by metalorganic chemical vapor deposition. The structural and optical properties were systematically studied by means of scanning electron microscopy, temperature- and excitation power-dependent photoluminescence (PL), PL excitation, and time-resolved PL spectroscopy. A 2DEG-related PL emission (P1) clearly appeared at about 70 meV below the GaN band-edge emission for the AlGaN/GaN structure with the low-temperature AIN interlayer. With increasing excitation power, we observed additional 2DEG-related emission peak (P2) at ~30 meV higher energy than P1. The carrier dynamics of these 2DEG emission peaks were investigated as a function of excitation power and temperature. The origin and carrier dynamics of these 2DEG emission peaks in AlGaN/GaN heterostructures with and without AIN interlayer will be discussed.

**Phosphor-Free White-Light InGaN/GaN Quantum-Well Light-Emitting Diode of Weak Quantum-Confined Stark Effects: Chi-Feng Huang; Chih-Feng Eu; Tsung-Yi Tang; Jing-Jie Huang; C. C. Yang; National Taiwan University**

We grew a white-light InGaN/GaN quantum-well (QW) light-emitting diode epitaxial structure with its electroluminescence spectrum close to the ideal condition (chromaticity diagram close to (1/3, 1/3) and a color temperature around 5600 K) in Commission International de l’Eclairage chromaticity based on the presynthesized metalorganic chemical vapor deposition technique. The prestrained growth leads to the efficient yellow emission from three InGaN/GaN QWs of increased indium incorporation. The color mixing for white light is implemented by adding a blue-emitting QW at the top of the yellow-emitting QWs. The blue shifts of the blue and yellow spectral peaks of the generated electroluminescence spectra are only 1.67 and 8 nm, respectively, when the injection current increases from 10 to 70 mA. Such small blue shifts imply that the piezoelectric fields or the quantum-confined Stark effects in our QWs are significantly weaker than those previously reported.

**Polychromatic Emission from Fluorescent-Microsphere-Coated LEDs: K.N. Hui; W.N. Ng; C.H. Leung; P.T. Lai; Hoi Wai Choi; University of Hong Kong**

Many on-going research efforts target the development of alternative phosphor-free white light generation, including CdSe quantum dots and multi-wavelength quantum wells. We present our solution to polychromatic light generation based on fluorescent microspheres, including CdSe quantum dots and multi-wavelength quantum wells.

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7th International Conference of Nitride Semiconductors
Remarkable Improvement of Output Power for InAlGaN Based Ultraviolet LED by Improving the Crystal Quality of AlN/AlGaN Templates: Takayoshi Takano; Sachie Fujikawa; Yukihiko Kondo; Hideki Hirayama; Matsubita Electric Works, Ltd.; Institute Physical and Chemical Research (RIKEN)

For the realization of commercially available low-cost and high-power ultraviolet light-emitting diodes (UV-LEDs), quaternary InAlGaN is very attractive, because highly efficient UV emission can be obtained due to In segregation effects. We achieved remarkable improvement of output power of 340 nm-band quaternary InAlGaN-based UV-LED and demonstrated high UV-output power by using high-quality AlN buffer templates on sapphire. Threading dislocation density for the edge type was 1.1×10^6 cm^-2 observed from the cross section transmission electron microscope (TEM) image. The output power of the 340 nm-band UV-LED was increased by approximately 7 times by reducing the FWHM of (10-12) x-ray o-scan rocking curve (XRC) from around 800 to 510 arcssec. As a result, we achieved maximum output power of 7.1 mW under RT CW operation. From these results, we found that the crystal quality of AlN/AlGaN templates strongly affects the output power of UV-LEDs.

Scanning Micro-Luminescence Spectroscopy of Commercial High-Intensity Blue InGaN LEDs: Lars Reissmann; Jürgen Christen; Thomas Hempel; Tanja Mesli; Jo Kunze; Andreas Kaluzsa; Rafael Jordan; Hermann Oppermann; OVG University Magdeburg

We report on scanning micro-luminescence (μ-EL) and micro-photoluminescence (μ-PL) spectroscopy measurements on blue InGaN-based high-power LEDs. We used LED-chips from two different manufacturers with peak wavelengths between 457-459 nm. Mounted chips were driven by DC forward currents of up to 1000 mA. The 324 nm line of a He-Cd-laser was used for PL excitation. The chip area of 1 mm^2 was scanned with spatial resolution of 8 μm down to 0.5 μm for selected areas. Both chips exhibit extraordinarily homogeneous spatial distribution of intensity and peak wavelength. The chips were subject to constant and cycling temperature treatments simulating aging processes. This resulted in massive degradation of light output power in the center of the chips. It is analyzed, whether structural defects in the semiconductor or mounting-related issues are responsible. YAG:Ce converter was applied and white LED modules with 4 chips and fluxes of up to 380 lm were fabricated.

Simulation and Design of InGaAsN Metal-Semiconductor-Metal Photodetectors for Long Wavelength Optical Communications: Shin-Li Tsai; Hung-Li Liao; Der-Yih Linn; Jing Yao Zheng; National Chianghua University of Education

Optical properties of InGaAsN metal-semiconductor-metal photodetectors (MSM-PDs) with modulation-doped heterostructures have been simulated by using an APSYS simulation program. Several structure parameters such as cap layer doping concentration, cap layer thickness, spacer layer thickness and absorption layer thickness are employed to study how these parameters change the photoresponse operating at a wavelength of 1.3 μm. A triangular well forms by combining InGaAsN with wide gap materials such as AlGaAs.

The two-dimensional electron gas (2DEG) is generated and localized at InGaAs-InGaAsN interface so that a larger effective Schottky barrier height can be achieved to reduce the dark current. The effective Schottky barrier heights, which extracted from experimental data, were used in our simulations for the different cap layer doping concentrations. Based on the simulation results the optimized design is proposed.

Surface Plasmon-Enhanced Light-Emitting Diode: Min-Ki Kwon; Ja-Yeon Kim; Baek-Hyun Kim; Il-Kyu Park; Chu-Young Cho; Chisu Byeon; Seong-Ju Park; Gwangju Institute of Science and Technology; Advanced Photonics Research Institute, Gwangju Institute of Science and Technology

Surface plasmons (SPs), excited on rough metallic surface by the interaction between light and metal are suggested to significantly enhance the light emission by improving the internal quantum efficiency. However, the realization of GaN-based LED structure with QW-SP coupling is not yet reported. Here, we demonstrate, for the first time, SP enhanced InGaN/GaN multiple quantum well (MQW) blue light emitting diode (LED) with an Ag nanoparticle layer inserted between n-GaN layer and MQW layer. The time resolved photoluminescence results clearly showed that the PL decay time of the blue LED with Ag nanoparticles is significantly faster than that of LED without Ag nanoparticles, indicating that spontaneous emission rate is increased with strong coupling between QW light emitters and SP of Ag nanoparticles. The optical output power of LED with Ag nanoparticles was increased by 32.2 % due to QW-SP coupling at an input current of 100 mA.

Temperature Dependence Intensity of 340 nm GaN/AlGaN Ultraviolet Light-Emitting Diodes: Koo Lee; Peter Parbrook; Tao Wang; Jie Bai; Fabio Ranalli; Qi Wang; Rob Airey; Geoff Hill; University of Sheffield

The temperature dependence (10-400K) of integrated electroluminescence (EL) intensity of 340nm GaN/AlGaN light emitting diodes is investigated and shows an anomalous ‘S’-shape behaviour. No correlation between this behaviour of EL intensity and exciton localization observed in the QW is found. We attribute the presence of an electron blocking layer as being the main reason for this behaviour. Above 250K, non-radiative recombination dominates and causes the decrease of the EL intensity as the temperature increases. However, between 150K and 250K, a decrease in EL intensity as the temperature decreases is observed due to the electron blocking layer preventing hole diffusion into the QW. As the temperature further decreases towards 10K a decrease in non-radiative recombination, leads to an increase in the intensity, assuming hole tunnelling through the blocking layer.

The AZO:Y2O3 Transparent Contact on InGaN/GaN MQWs LEDs: Chi-Li Cheng; Wei-Chih Lai; Cheng-Huang Kuo; Jinn-Kong Sheu; Shou-Jin Chang; Institute of Electro-Optical Science and Engineering, National Cheng Kung University; Department of Optics and Photonics, National Central University; Institute of Microelectronics, National Cheng Kung University

The internal quantum efficiency and light extraction efficiency are two issues to get high efficiency LEDs. To get more light extraction efficiency the ITO transparent contact was widely used for the transparent contact of GaN based LEDs instead of Ni/Ag transparent contact. ZnO based materials were also the candidates of transparent contact for the GaN based LEDs. In our study the AZO:Y were used for the transparent contact of the GaN based LEDs. The forward voltage of LEDs with AZO:Y driving at 20mA was about 3.55V and was about 0.17V higher than the LEDs with ITO. The current-voltage and power-current characteristics were shown on figure 1 and 2 respectively. The GaN based LEDs with AZO:Y has got the output power around 10% more than the GaN based LEDs with ITO.

Time-Resolved Electro-Luminescence Studies of InGaN Blue LEDs with Chip Size Variations: Shih-Wei Peng; Tzong-Liang Tsai; Wen-How Lan; C. J. Huang; Ming-Chang Shih; National University of Kaohsiung; Huga Optotech Inc.

InGaN-based light emitting diodes (LEDs) are promising candidates for applications in large-screen display, signage, and solid-state lighting. Time-resolved electro-luminescence (TREL) is a powerful tool to investigate the carrier dynamics. In this study, we will report carrier dynamics of three InGaN Blue LEDs with chip size variations by using TREL measurements. Three samples with the same structures but different chip sizes were compared. For the largest chip size sample, the EL spectrum was smaller and the delay-times (response times) were longer than those of the other samples. It implies that the current spreading for larger chip size need more time. Rise-times and decay-times of the three samples will also be compared. In the future, carrier dynamics and luminescence mechanism will be presented in the conference.

Transport Properties in n-Type AlGaN/AlN/GaN-Superlattices: Joachim Hertkorn; Peter Brückner; Chong Gao; Ferdinand Scholez; Ulm University

In order to improve the lateral conductivity in optoelectronic devices, we have investigated Si-doped AlGaN/AlN/GaN-superlattices. As a first step we performed calculations of the band structure of AlGaN/AlN/GaN modulation doped multi heterostructures. Based on these results we worked on optimizing the growth of low Al content (xAl < 20%) superlattices by MOVPE. Several tens of abrupt and graded AlGaN/AlN/GaN-layer pairs could be grown crack-free on 2 μm thick n-GaN layers deposited on sapphire substrates with AlN nucleation. By Van-der-Pauw Hall measurements, we determined that...
the lateral conductivity of a 1.5 μm thick superlattice structure is a factor of four higher than in highly n-doped bulk material with comparable thickness without compromising too much the vertical conductivity as confirmed by two step TLM-measurements. At 77 K we could demonstrate an extremely high effective mobility of 14720 cm²/Vs at n=8x10¹⁷ cm⁻³ (R=1.7 Ω), a clear verification of our excellent crystal quality.

**UV-LED Efficiency Enhancement Using Freestanding GaN Substrate**

Markus Maier; Klaus Köhler; Michael Kunzer; Joachim Wegert; Shiangji Liu; Ulrich Kaufmann; Hans-Joachim Wagner; 1Fraunhofer Institute for Applied Solid-State Physics

Freestanding GaN-substrates with low defect density (DD) are not only the key to reduce threshold current densities and prolong lifetimes of blue laser diodes, but also enhance the output power of blue LEDs. To study the effect of the DD on short-wavelength LEDs, we have grown LEDs structures by MOVPE, emitting in the 370–420 nm range, on sapphire, low dislocation templates (ULD) and freestanding GaN, with a DD ranging from 10⁹ cm⁻² to 5x10⁷ cm⁻². A clear increase in output power upon reduction of the DD is observed, being strongest for wavelengths shorter than 390 nm. Comparing the output power of LEDs on different substrates, special attention has to be paid to differences in light extraction efficiency. Though band-to-band absorption limits the use of freestanding GaN to wavelengths exceeding 380 nm, it offers the possibility to significantly enhance the light extraction via backside surface texturing. [http://compoundsemiconductor.net/articles/](http://compoundsemiconductor.net/articles/)

*Cambridge University; 2Ceramic Operation, Ibiden Company Limited; 3Corporate R&D Center, Showa Denko K.K*

We fabricated UV-LED on 3 types of the underlying layers. All samples were grown on AIN on sapphire substrates by MOVPE. Type 1 is UV-LED on AIN template. Type 2 is ELO AlₐGa₁₋ₐN on AIN. Type 3 is ELO AlₐGa₁₋ₐN on grown AlN. We compared how different operation wavelengths influenced by the difference of the underlying layer. Light output intensity of UV-LED fabricated on ELO AlₐGa₁₋ₐN on grown AlN is stronger than that of other samples from the L-I curves. The improvement of this luminescence intensity originates in a decrease in the defect in AlGaN and control of strain.

**Voltage Tunable Wavelength Light Emitting Diode**

Chew Beng Soh; Soo Jin Chua; Haryono Hartono; 1Institute of Materials Research and Engineering

We report on the growth and fabrication of a LED which emits light, tunable in color, ranging from red, yellow, green and cyan as the input voltage is increased. Two multiple quantum well (MQWs) structures, designated as A and B, are grown in the LEDs, with quantum dots embedded in MQWs A. The InGaN/GaN layers are grown by MOVCD with sapphire as the substrate. A broad photoluminescence spectrum ranging from 500 nm to 700 nm is measured, which is the result of broadening attributed to the incorporation of quantum dots in the well layer of MQWs A. The emission peak at 433 nm (blue emission) is from the MQWs B. The 3D confinement in the quantum dots reduces the effective piezoelectric field effects, despite the thicker well layer of approximately 4.5 nm. To enhance the light extraction, a porous-like p-InGaN layer is grown to form the p-contact layer.

**Wafer-Scale Electroluminescence Studies on GaN-Based LED Structures**

Carmen Salcianu; Ted Thrush; Clifford McAleese; Colin Humphreys; 1Cambridge University

Electroluminescence testing of LED structures is usually done at the chip level. However reliable screening of complete wafers for their optical and electrical characteristics would improve the cost effectiveness of producing LED-lamps. This paper will present wafer scale optoelectronic data, measured using both probe contacts and temporary “adherent” contacts. Although such measurements have provided a useful insight into epilayer quality, developments are still needed both in the methodology of the characterisation technique and in the design of the grown LED structures if a reliable assay of the wafer’s device potential is to be realised. Improvements in the reproducibility of the method have resulted from better techniques for forming the n-type contact, as well as changes to the grown p-type capping layer which have improved its “contactability.” The latter was achieved using either a p-type superlattice or a highly doped p-GaN layer on top of the standard p-capping layer.

**Well Width Dependent Luminescence Characteristics of UV-Violet Emitting GaInN QW LED Structures**

Michael Kunzer; Columbia Leaneu; Markus Maier; Klaus Köhler; Ulrich Kaufmann; Joachim Wagner; 1Fraunhofer Institute for Applied Solid-State Physics

Temperature and excitation power dependent photoluminescence spectroscopy on GaInN UV-violet LED structures allows to separate the influence of the quantum confined Stark effect (QCSE) from carrier localisation in In-induced band tail states as well as to determine the internal quantum efficiency (QE). A LED series with different quantum well widths (1.3-7nm) was grown by MOVPE on sapphire, low defect density (LDD) GaN templates and free standing GaN substrates. The photoluminescence data reveal, that the QCSE cannot be neglected even for low In-content (<10%) UV (<400nm) LED structures. Upon growth on LDD substrates, the internal QE is considerably increased for short wavelength (375-400 nm) LEDs. Furthermore, the effect of the QCSE on the current dependence of the QE has been studied by pulsed electroluminescence measurements, where a pronounced non-thermal rollover of the QE with increasing current density is observed at wavelengths >390 nm.

**Characteristics of InGaN Designed for Photovoltaic Applications**

Elakesa Trybav; Omkar Jari; Shawn Burnham; Jing Bai; David Crittin; Ian Ferguson; Christina Honberg; Myles Steiner; W. Alan Doolittle; 1Georgia Institute of Technology; 2University of Delaware; 3National Renewable Energy Laboratory

This work addresses the required properties, device structures, and measured results for an InGaN solar cell. Homojunction InGaN solar cells with a bandgap greater than 2.0 eV are specifically targeted due to discussed cell design and material limitations. These devices are attractive because over half the available power in the solar spectrum is above 2.0 eV. Using high growth rates, InGaN films with In compositions from 1-32% have been grown by Molecular Beam Epitaxy with negligible phase separation according to X-ray diffraction analysis, and better than 190 arcsec omega-2theta FWHM for ~0.6μm thick InₓGa₁₋ₓN film. Using measured transmission data, the absorption coefficient of InGaN at 2.4-eV was calculated as α = 2x10⁵ cm⁻¹ near the band edge. This results in the optimal solar cell thickness of ~500nm and may lead to high open circuit voltages and will also lessen the constraints on limited minority carrier lifetimes.

**Control and Formation of GaN Nanoparticles on Polar GaN and SiC for GaN Nanostucture Growth**

Pae Wu; Maria Losurdo; Tong-Ho Kim; Giovanni Bruno; April Brown; 1Duke University; 2Institute of Inorganic Methodologies and of Plasmas-CNR

Investigation of GaN nanostucture growth is of great import for development of nanoscale nitride semiconductor devices. GaN nanowires have been grown by the vapor-liquid-solid (VLS) growth mechanism [J. Electroceram. (2006) 17, 903–907] requiring the self-assembly of Ga droplets on the growth surface in which precursor gas is diluted before the precipitation and formation of GaN nanostuctures [J. Am. Chem. Soc. (2001) 123, 2791-2798]. Through use of in situ spectroscopic ellipsometry to probe the surface plasmon resonance of Ga nanoparticles (NPs) deposited by molecular beam epitaxy onto polar GaN and SiC substrates, we demonstrate the formation and control of Ga NPs. X-ray photoelectron spectroscopy and atomic force microscopy reveal that the resultant Ga NP morphology is dependent on the SiC or GaN polarity and surface charge. The chemical and physical properties of these GaN NPs are then correlated with their formation mechanism.
physical interaction between the SiC or GaN substrates with the Ga NP s is important for VLS GaN nanostucture growth.

Correlation between Chemical and Electrical Properties of P-GaN Surfaces Subjected to Halogen-Based Plasma: Eri Ogawa1; Masahiro Sugimoto2; Tetsu Kachi3; Tsutomu Uesugi4; Narumasa Soejima5; Tamotsu Hashizume6; RCIQE, Hokkaido University; 7Toyota Motor Corporation; 7Toyota Central R&D Laboratories, Inc

The chemical and electrical properties of the plasma-treated p-GaN surfaces were systematically characterized by X-ray photoelectron spectroscopy (XPS), I-V and C-V analyses using Schottky contacts, and Hall method. The XPS analysis showed the peak shifts of the core levels in the Ga-N bonds for the Cl25+ and CHF3 plasma treated samples, in comparison with the as-grown sample. Moreover, the GaCl4− and GaF2− components were detected on the processed p-GaN surfaces, respectively. In the I-V characteristics between the Ni/Au electrodes evaporated on the p-GaN surfaces, a larger on-set voltage was observed for the Cl2-plasma sample, as compared to the as-grown sample. The formation of thin GaCl4− component on p-GaN seems to enhance the Schottky barrier height. For the CHF3-plasma sample, on the other hand, we observed the increase in resistivity of the p-GaN surface, indicating that the incorporation of F atoms into GaN may cause a compensation of holes.

Effects of Carbon Diffusion on Electrical and Optical Properties of N-GaN: Takeshi Kimura; Tamotsu Hashizume; Hokkaido University

Using SiN/CN, bilayer structure prepared by electron-cyclotron-resonance assisted chemical vapor deposition, a simple process of carbon diffusion into GaN layer was developed. The thin CN layer with a highly carbon-rich composition can act as source for carbon diffusion. An x-ray photoelectron spectroscopy and a secondary ion mass spectrum results showed diffusion of carbon with into GaN a depth of about 200 nm after an anneal at 1000 °C for 120 min in N2 ambient. The Photoluminescence spectra showed that the deep-level-related emission was enhanced by the carbon diffusion, while no pronounced emission was observed from the shallow acceptor levels in the carbon-diffused sample. We also observed the increase in resistivity of the GaN surface after the carbon diffusion. These results indicate that the diffused carbon acts as a deep acceptor in the form of an interstitial atom or in the complex form with some defects in GaN.

Evolution of Surface Morphology during Crystallographic Wet Etching of N-Type GaN Using Phosphoric Acidic Solutions: Jae Kwan Kim; Taek Seung Kim; Youngie Jo; Han-Ki Kim; Sang-Woo Kim; Kyoung-Kook Kim; Ji-Myon Lee; Sunchon National University; Kumoh National Institute of Technology; Samsung Advanced Institute of Technology

The morphology variation of the etched surface by using phosphoric acidic solution was observed by optical microscopy and atomic force microscopy. Initially, high density of hexagonal holes or pits were formed on the etched surface, with the lateral size of 20 μm or 5 μm, respectively, indicating that the crystallographic etching was occurred. However, as the etching time was increased further, the lateral size of the hexagonal holes or pits was increased, and finally, joined and merged together at the time of 100 min. This means that the etching of n-type GaN by phosphoric acidic solutions proceeded through the lateral widening and the merging of initial holes and pits. Furthermore, fundamental mechanism of initial stage of etching of n-type GaN using phosphoric acidic solutions will be reported in this presentation.

Fabrication and Stress Relief Modelling of GaN Based MEMS Test Structures Grown by MBE on Si(111): Eugenio Sillero; David López-Romero; Ana Bengoechea; Miguel Angel Sánchez-Garcia; Fernando Calle; ISOM & DIFUPM

The fabrication of III-N MEMS and the modelling of their residual stress induced deformation is presented. GaN and AlGaN/GaN test structures were fabricated, either with one end and both ends clamped to the Si substrate. The residual stress in the III-N layer were measured by photoluminescence and X-ray diffraction, and the stress relief induced deformation was analysed by a finite element model method. One-end-clamped structures suffer from large deformations due to the uneven stress relaxation. During micromachining, the relaxation induces large upward buckling, as measured for fabricated devices and fitted by the FEM model. Two-end-clamped structures were also studied using different topologies and under-etching lengths of the clamped region. It is concluded that the deformation of such structures may be reduced if symmetrical mechanical boundary conditions are provided, and the under-etching of the clamping region is small compared to the device dimensions.

Formation of Nitride Laser Cavities with Cleaved Facets on Transferred Laser Diodes on GaAs Substrates: Wen-Chien Yu; Shu-Mei Ye; Feng-Ke Hsiao; Chi-Ling Lee; Wei-I Lee; Pei-Lun Wu; Chiao Tung University

Smoothly cleaved facets with high reflectivities have been demonstrated on GaN laser diodes after the devices were transferred onto GaAs substrates. The GaN based laser diode structure was first fabricated by metal organic chemical vapor deposition (MOCVD) on e-plane sapphire substrates. The samples were then mounted onto thin GaAs substrates using wafer-bonding technology. Laser liftoff (LLO) technique was applied to remove the original sapphire substrate and transfer the GaN laser structure onto GaAs substrates. Since the cubic substrates have well-defined laser cavity cleavage facet, the GaN structures bonded onto the substrates also formed smooth facets after cleavage. The cleaved facets of GaN laser diodes have been characterized using atomic force microscopy (AFM) with less than 3 nm roughness. The present study demonstrated the feasibility of transferring GaN laser structures onto other more appealing substrates for formation of laser cavities.

Gentle Chemical Mechanical Polishing of GaN Substrates: Rajiv Singh1; Arul Chakkaravarthi Arjunan; Hung-Ta Wang; Stephen Pearton; Sahil Sahni; Fan Ren; Syamal Lahiri; Deepika Singh; University of Florida; Simmat Inc

As GaN is chemically inert and mechanically hard, existing polishing techniques have typically employed hard particles or incompatible chemistries. Such polishing solution results in rough or damaged and scratched layers. We have developed a industrially robust and low cost chemical mechanical smoothing (CMS) process to produce atomically polished GaN substrates. Such atomically polished GaN on silicon substrates are expected to increase device yield, help development of novel device structures and enhance technical performance of GaN based devices. Our results show that the GaN surfaces can achieve atom level smoothness and formation of a high quality surface. The rms roughness decreased from 4.1nm to less than 1Å after the polishing process. The Schottky devices made from CMS polished substrates shows lower leakage current and large barrier height confirming the removal of the defective surface layer. The formation of such surfaces is expected to be ideal for GaN based electronic devices.

High-Quality Native Oxide of GaN for Surface Passivation Formed by Photo-Enhanced Electrochemical Process: Nanako Shiozaki; Fumitaro Ishikawa; Achim Trampert; Holger Grahn; Tamotsu Hashizume; Hokkaido University; Paul-Drude-Institut für Festkörperforschung

This paper reports on successful oxidation of n-GaN surface using photoelectrochemical process in a mixed solution with propylene glycol and 3% tartaric acid. To oxidize the GaN surface, we first applied ramp-type bias from 0 to 3V and then constant bias at 3V under the potentiostatic control. The process with this bias form enables us to form high-quality native oxide of GaN which has thin crystalline intermediate layer at oxide/GaN interface. Photoluminescence coming from oxidized GaN surface showed 3 times higher intensity than that from un-oxidized area of the sample. The consumption of the GaN surface to form the native oxides may result in the reduction of various kinds of surface defects, leading to the drastic reduction of surface states on the oxidized GaN surfaces. This oxidation method will be useful for stability improvement of LDs and HBTs.

Impact of AlN Interlayer on the Transport Properties of AlGaN/GaN Heterostructures Grown on Silicon: Said Elsheimi; W. Mitchell; R. Berney; M. Ahoujja; J. Roberts; P. Rajagopal; J. Cook; E. Piner; K. Linthicum; University of Dayton; Air Force Research Laboratory; Nitronex Corporation

Hall and Shubnikov-de Haas effects measurements were performed to identify the impact of inserting a 1nm AlN interlayer between AlGaN and GaN. The transport properties of this AlGAN/AIN/GaN structure were compared to the conventional structure (AlGAN/GaN). Our measurements indicate the AlN interlayer resulted in improved transport in the temperature
range studied (300 K-1.2 K). However, the impact of the AlN layer was found to be much more significant at low temperatures. The improvement is believed to be the result of reduced alloy scattering arising from a stronger confinement of the 2DEG. At 300 K the carrier density and mobility for the AlGaN/AlN/GaN structure were roughly 1.00 x 10^13 cm^-2 and 1937 cm^2/Vs. Whereas those of the conventional structure were 8.57 x 10^12 cm^-2 and 1523 cm^2/Vs. Shubnikov-de Haas oscillations were observed in both samples at low T.

**Improvement of Hydrogen Generation Efficiency Using GaN Photoelectrochemical Reaction in Electrolytes with Alcohol.** Katsushi Fujii; Hitoshi Nakayama; Keiichi Sato; Takashi Kato; Meoungwhan Cho; Takafumi Yao; Tohoku University

Photoelectrochemical water reduction is one of the candidates for hydrogen production by solar energy. GaN is superior to many oxides like TiO_2 in terms of efficiency, since the conduction band energy is more suitable for hydrogen generation. In this report, we discussed the effect of organic addition to an electrolyte for hydrogen generation without bias. We used 1.0 mol/L NaOH as an electrolyte with and without 1.0 mol/L CH_3OH or CH_2OH. The current densities were almost the same at the beginning (0.88 mA/cm^2 for NaOH, 0.99 mA/cm^2 for NaOH with CH_3OH, 0.81 mA/cm^2 for NaOH with CH_2OH under 310 mW/cm^2 illumination). The photocurrent densities with alcohol decreased and almost stabilized after 200 min, while the density without alcohol decreased linearly. Hydrogen generations with alcohol were approximately double of that without alcohol where the total charges are almost the same at 300 min.

**Improvement of the Light Output Power of GaN-Based LEDs by Using Interlayered Indium Tin Oxide-Based P-Type Electrodes.** June-O Song; Hyun-Gi Hong; Hyoenseok Na; Tae-Yeon Seong; National Institute for Materials Science; Korea University

To enhance the light output of GaN-based LEDs, transparent indium tin oxide (ITO) and ZnO-based schemes have been investigated. However, single ITO single contacts showed rather poor electrical behavior because ITO has a relatively small work function (4.8eV). Thus, in this work, to improve its electrical properties, we have introduced different interlayers of In and SnAg alloy. The In/ITO and SnAg/ITO contacts become ohmic with specific contact resistance of 1.2x10^-4 to 4.2x10^-7 ohm/cm^2 and transmittance of 91–95% at 460 nm when annealed at 530°C. Blue LEDs fabricated with the In and SnAg/ITO contacts give forward-bias voltage of 3.31–3.42V at injection current of 20 mA. LEDs fabricated with these interlayered ITO p-type contact layers exhibit much better output power (e.g., improvement by 20% of forward voltage of 3.31–3.42V at injection current of 20 mA) compared to that of LEDs with the oxidized Ni/Au contacts. Possible ohmic mechanisms are described and discussed.

**Doping of the Optical Performance of GaN-Based LEDs by Using Cu-Doped Indium Oxide/Sh-Doped SnO_2 P-Contacts.** Hyun-Gi Hong; Hyoenseok Na; Joon-Ho Oh; Kang-Won Kim; Ju-Heon Yun; Yong-Hyun Kim; Joon-Woo Jeon; Yoon-Han Kim; Tae-Yeon Seong; Korea University

Currently, indium tin oxide(ITO) is commonly used for p-type electrodes in GaN-based LEDs because it has high conductivity and transmittance. ITO, however, suffers from thermal instability and the exhaustion of indium. In this work, we have investigated Cu-doped indium oxide(CIO/Sh-doped SnO_2:ATO) p-contacts to improve the optical performance of LEDs. It is shown that the CIO/ATO/250 nm) contacts become ohmic with specific contact resistance of 2.1x10^-3 ohm cm^2 and exhibit transmittance of ~81% at a wavelength of 400 nm when annealed at 360°C. Furthermore, near-UV LEDs(400 nm) with the CIO/ATO contacts show higher output power than LEDs with conventional Ni/ Au contacts. For example, LEDs with the 630°C-annealed CIO/ATO p-contacts result in improvement (by 82.4%) of the output power at 20mA compared to LEDs with Ni/Au p-contacts. Based on XPS and AES results, possible ohmic formation mechanisms are described.

**Optimization of Ohmic Contacts to N+-GaN Capped AlGaN/AlN/GaN HEMTs.** Liang Wang; Sith Mohrmededdin Oifuonye; Ihesanni Adesida; University of Illinois at Urbana-Champaign

Optimization of Ti/Al/Mo/Au ohmic contacts to n+–GaN/AlGaN/ GaN heterostructures is reported. The contact performance, as obtained from I-V linearity, and contact resistance, of as-deposited and annealed contacts depends on SiC14 plasma self-bias voltage, heat treatment condition, and Ti thickness. For the 15 nm-Ti scheme, optimum Re=0.46 O-mm was achieved by a combination of 400 V, 1 min plasma treatment and 850°C, 30s annealing. However, untreated sample showed linear I-V curve but with Re=1 O-mm. Doubling the Ti thickness reduced Re and Re=0.5 O-mm was obtained for both plasma treated and untreated samples. Optimum performance was achieved with a plasma bias of 300 V followed by 850°C annealing. XTEM investigation indicated that 15 nm-thick Ti reacted only with the GaN cap and the AlGaN layer remained intact. However, 30nm-thick Ti effectively thinned down both GaN cap and the top part of AlGaN so that higher tunneling current was enabled.

**Photoelectrolysis of Water with Structured N-GaN.** Ichitaro Waki; Daniel Cohen; Rakesh Lai; Umesh Mishra; Steven DenBaars; Shuji Nakamura; University of California, Santa Barbara

Direct water photoelectrolysis with semiconductors has attracted attention as a hydrogen production technology. Recent demonstrations of water photoelectrolysis with GaN showed the potential, but the solar-to-hydrogen conversion efficiency is not sufficient for practical use. In this study we observed more efficient direct water photoelectrolysis using a structured n-GaN photoanode and a platinum cathode without external bias. The structured n-GaN was formed by a metal stripe patterning using photolithography and a subsequent selective area regrowth. As expected, the photocurrent of the structured n-GaN was significantly enhanced in comparison with a plane n-GaN particularly at higher current densities. We attribute the enhancement to both alleviated current crowding and increased specific surface area. A gas volume analysis showed evidence of hydrogen and oxygen evolution. The origin of the photocurrent and the conversion efficiency will be discussed in detail based on water-splitting reactions and etching reactions.

**Properties of ZnO Layers Grown by Metalorganic Chemical Vapor Deposition on GaN(0001) Templates and ZnO(0001) Substrates.** Tommy Ives; Tammy Ben-Yaacov; Hirokuni Asamizu; Umesh Mishra; Steven DenBaars; James Speck; University of California, Santa Barbara; Rohm Company

We study the properties of ZnO(0001) layers grown by metalorganic chemical vapor deposition on GaN(0001) templates and ZnO(0001) substrates. The layers grown homoepitaxially on ZnO substrates yield excellent results in terms of surface morphology and crystal quality. ZnO layers grown on GaN templates are smooth but exhibit pits and plateau-valley or fractal morphology with a root mean square value of 2.0 nm. The full width at half maximum of symmetric omega scans were as narrow as 288 arcsec. X-ray rocking curves recorded in skew geometry had a full width at half maximum of 936 arcsec or higher. Reciprocal space maps show that the...
ZnO layers grown on GaN layers are relaxed. No mismatch was detected for the layers grown homoepitaxially. Unintentionally doped ZnO layers were grown on (In,Ga)N LEDs in an attempt to use ZnO as a transparent contact.

**Thermal Analysis of GaN Powder Formation via Reaction of Gallium Ethylenediamine Tetraacetic Acid Complexes with Ammonia:** Yuhuai Liu; Shinya Koide; Hideto Miyake; Kazumasa Hiramatsu; Atsushi Nakamura; Nobuyoshi Nambu; 1Mie University; 2Chubu Chelest Company, Ltd

The gallium ethylenediamine tetraacetic acid (Ga-EDTA) complexes were analyzed by thermal gravity/differential thermal analysis (TG/DTA) under ammonia gas flow to reveal the mechanism of GaN powder formation via reaction of Ga-EDTA complexes with ammonia. The results of the dynamic TG/DTA and the thermal sintering temperature/time dependence show that the precursors undergo a sharp mass loss at about 296°C due to the release of organic groups, followed by further releasing of organic groups (297 ~ 552°C), elimination of carbon and formation of GaN (552 ~ 650°C), GaN crystallization and further elimination of carbon (650 ~ 850°C), the improvement of GaN crystal quality (600 ~ 1100°C) and the initial decomposition of GaN powders. The analysis of the results indicates that proper sintering temperature for GaN powders should be approximate to 1100°C.

**Thermal Conduction in Nitride Semiconductors and GaN-Based Device Structures:** Alexander Balandin; 1University of California - Riverside

Self-heating presents a major problem for the high-power density GaN-based field-effect transistors. Optimization of GaN devices requires knowledge of thermal conductivity K in GaN films and AlxGa1-xN alloys. There is major discrepancy in the reported K values ranging from 1.30 to 2.25W/mK at RT. The theoretically predicted maximum is K=4.10W/mK at RT. In this talk I will review our results, which explain K dependence on the defects, dislocations and alloy disorder. Our measurements were carried out using transient techniques. The theoretical analysis is based on the Callaway – Klemens and Abeles models. I will also report the electro-thermal simulations of the GaN device performance focusing on self-heating and ambient effects. 1J. Zou et al, J. Appl. Phys., 92, 2534 (2002); Appl. Phys. Lett., 79, 4316 (2001); W.L. Liu and A.A. Balandin, J. Appl. Phys., 97, 073710 (2005). 2V. O. Turin and A.A. Balandin, J. Appl. Phys., 100, 054501 (2006).
8:30 AM Invited

**KK1, P-Type InN and In-Rich InGaN:** Joel Ager; Lawrence Berkeley National Laboratory

The bandgap range of InGaN extends from the near-IR (InN, 0.65 eV) to the ultraviolet. To exploit this wide tuning range in light generation and conversion applications, pn junctions are required. The large electron affinity of InN (5.8 eV) leads to preferential formation of native donor defects, resulting in excess electron concentration in the bulk and at surfaces and interfaces, which creates difficulties for p-type doping and/or measuring of the bulk p-type activity. Capacitance voltage measurements, which deplete the n-type surface inversion layer, have been used to show that Mg is an active acceptor in InN and In-rich InGaN. Recent investigations of the properties of Mg-doped InN and InGaN will be presented, including thermopower transport measurements and photoelectroluminescence. In collaboration with R. E. Jones, N. Miller, K. M. Yu, J. Wu, W. J. Schaff, and W. Walukiewicz.

9:00 AM Invited

**KK2, Electrical Properties of p-Type N-Polar InN Grown by RF-MBE:** Daisuke Muto; Hiroyuki Naoi; Shinji Fukumoto; Kin Man Yu; Nate Miller; Rebecca Jones; Joel Ager; Eugene Hailer; Tsutomu Araki; Yasushi Nanishi; Wladek Walukiewicz; Iwate University; Lawrence Berkeley National Laboratory

P-type N-polar InN films have been grown for the first time by RF-MBE using Mg as a dopant. The Mg content was varied by controlling the Mg cell temperature in the range of 125-140 °C. Electrical properties were evaluated by electrolyte-based C-V measurements. From the 1/C-V (Mott-Schottky) plots, it was found that Mg-doped InN grown with a Mg cell temperature of more than 130 °C is p-type under a surface inversion layer. We also found that the p-type Mg-doped InN tends to have a higher net acceptor concentration as the Mg doping amount is increased. This result indicates that the p-type conductivity of InN can be controlled by changing the Mg cell temperature. This technique may be useful in the fabrication of InN-based opto-electronic devices in the future.

9:30 AM

**KK3, P-Type Doping of InN:** Thomas Myers; Craig Swartz; Chito Kendrick; Phil Anderson; Hai Lu; Sandeep Chandril; Y. Song; Roger Reeves; Steve Durbin; William Schaff; West Virginia University; Cornell University

Of current interest is the possibility to achieve p-type conductivity in InN. The surface electron accumulation layer can mask a p-type layer’s contribution to conventional Hall effect measurements. Variable magnetic field Hall measurements can be used to determine the influence of the various carriers. Temperature dependent resistivity and Hall measurements were made at magnetic fields up to 12 T on InN samples grown by molecular beam epitaxy. Quantitative mobility spectrum analysis (QMSA) and multiple-carrier fitting analyses were performed. Evidence will be presented for direct observation of p-type doping of InN in samples doped in-situ with Mg and via substrate impurity doping when growing on (111) YSZ. QMSA reveals light hole conduction in many of the samples, with one sample clearly p-type, exhibiting both heavy and light holes. At Mg concentration of 6x1018cm-3, a faint PL peak at 0.56 eV suggests an acceptor energy approximately 110 meV above the valence band.

9:45 AM

**KK4, Study on P-Type Dopability and Polarity Inversion in Mg-Doped In-Near-InN:** Xingjiang Wang; Song-Bek Che; Yoshihiro Ishitani; Akihiko Yoshikawa; Graduate Course of Electrical and Electron Engineering, Venture Business Laboratory, In-N Project as a CREST-program of JST, Chiba University

Mg-doped InN films are grown under In-polarity regime with systematically varied Mg-beam fluxes by MBE. It is found by SIMS analysis that Mg concentration is linearly proportional to Mg-beam flux, indicating that Mg sticking coefficient is almost unity up to 1.8x1020 cm-3. Electrical, crystalline and optical properties of InN films are greatly influenced by Mg-doping. With increasing Mg beam flux, electron concentration in InN decreases first by the effect of carrier compensation, and then begins to increase due to the formation of Mg-related donor-like-defects. In the partially carrier-compensated Mg-doped InN, two photoluminescence peaks are observed. The excitation power dependent PL study indicates that one emission peak is originated from free-to-acceptor emission with acceptor activation energy of about 61 meV and the other is due to the band-to-band emission. Furthermore, In-polar InN is found to be inverted to N-polar one when Mg concentration is larger than 2.9x1019cm-3.

10:00 AM

**KK5, Determination of the Mg Occupation-Site in MOCVD-Grown Mg-Doped InN by Using X-Ray Absorption Fine-Structure Measurements:** Takao Miyajima; Shigeaki Uemura; Yoshihiro Kudo; Yoshihito Kitajima; Akio Yamamoto; Sony Corporation; High Energy Accelerator Research Organization; Fukui University

InN-based devices with a p-n junction have not yet been realized because it is difficult to obtain low-resistivity p-type InN. When Mg, which is a prime candidate for a p-type dopant, is doped to InN, the conductivity has been n-type or insulating. In order to determine what prevents p-type conductivity, it is necessary to determine the Mg occupation-sites. For this, we analyzed the atomic structure around Mg atoms in Mg-doped InN by using Mg K-edge x-ray absorption fine-structure (XAFS) measurements. Our experimental data fit to the simulated data in which Mg atoms occupy the substitutional sites of In atoms. From this result, we conclude that Mg atoms essentially occupy not N atoms sites but In atoms sites, meaning that Mg atoms can act as acceptors in InN. We believe that observations of p-type conductivity are prevented by the remaining problems such as carrier compensation and electron accumulation at the surface.

10:15 AM

**KK6, Surface Electronic Properties of N- and P-Type InN and InGaN Alloys:** Philip King; Tim Veal; Paul Jefferson; Hai Lu; William Schaff; Chris McConville; University of Warwick; Cornell University

The variation of band bending as a function of composition at (0001) surfaces of undoped and Mg-doped InGa_N is investigated using x-ray photoelectron spectroscopy. Distinctly different trends in barrier height are observed for the Mg-doped compared to undoped alloys, explained in terms of Fermi-level pinning at the surface and virtual gap states. Solutions of Poisson’s equation within the modified Thomas-Fermi approximation are used to model the band bending and corresponding variation of carrier concentration with depth below the surface. For undoped alloys, a transition from electron accumulation at In-rich to depletion at Ga-rich alloys occurs at x=0.3, whilst for Mg-doped alloys, a transition from a surface inversion layer for In-rich to a surface hole depletion layer for Ga-rich alloys occurs at x=0.49. The trend in barrier height across the composition range and calculated space-charge profiles indicate that Mg-doping induces bulk p-type conductivity across the entire composition range.

10:30 AM Break
Technical Program

Session LL: Nanostructures: Growth I

Friday AM  Room: 313/316  Location: MGM Grand Hotel Conference Center

8:30 AM Invited

LL1. Nitride Nanowires and Nanotubes: Peidong Yang; University of California, Berkeley


9:00 AM

LL2. Fabrication of Patterned InN Nano-Columns by ECR-MBE: Tsutomu Araki; Taihei Yamaguchi; Satoshi Harui; Hideto Miyake; Kazumasa Hiramatsu; Yasushi Nanishi; Ritsumeikan University; Mie University

InN-based nano-structures are very attractive for applications to long-wavelength optoelectronic devices. Recently, we have proposed a novel growth technique of position-controlled InN nano-dots on the GaN template with patterned holes prepared by using FIB. In this study, we will demonstrate successful fabrication of patterned InN nano-columns on the hole-patterned GaN templates using ECR-MBE. InN growth was carried out at 450°C for 2 hours on the GaN templates with square arrays of holes prepared by FIB. We successfully obtained the patterned InN nano-columns with a well-ordered height of ~1.5 μm and a diameter of ~200 nm. InN nano-columns showed hexagonal structures with the same in-plane orientation, indicating that InN nano-columns with [0001] growth direction were epitaxially grown on the (0001) GaN template. TEM studies also confirmed that few threading dislocations were observed in these InN nano-columns. These results indicate that this growth technique is very useful for fabricating periodic InN-based nano-structures.

9:15 AM

LL3. Self-Organized Growth of Inn-Nanocolumns by MBE: Christian Denker; Florian Werner; Joerg Malindretos; Henning Schuhmann; Michael Seibt; Angela Rizzi; Jaime Segura; Nuria Garro; Andres Cantarero; Georg-August-Universitaet Goettingen; University of Valencia

InN-nanocolumns are an attractive system for light harvesting applications. Our aim is to investigate the growth, optical and electrical properties of nanocolumn ensembles and single objects. The samples were grown on p-Si(111) by plasma assisted MBE. Depending on the growth parameters different growth regimes for nanocolumns were identified according to their final shape: hexagonal cross-section and broadened end, rounded cross-section and tapered end. For certain growth conditions we reproducibly observe a bimodal distribution in which one type of wires shows a very high aspect ratio of 45. The early stages of nucleation have been analyzed and correlated to the final shape distribution. High-resolution TEM images show a very good crystal quality, with features that depend on the growth mode. This fact is also reflected in photoluminescence and Raman analysis.

Furthermore we will present I-V-characteristics of single nanocolumns in two- and four-point probe geometry.

9:30 AM

LL4, InGaN Nanostructured Materials: Controlled Synthesis, Characterizations, and Applications: Olga Krylovsk; Josh Mangum; Hyun Jong Park; YongSun Won; Tim Anderson; Zuzanna Liliental-Weber; University of Florida; Lawrence Berkeley National Laboratory

Controlled synthesis of 1D III-Nitrides creates an opportunity for their fundamental study and new applications for future electronic and photonic devices. Single-crystalline InGaN nanorods (NRs) and nanowires (NWs) were successfully grown on Al2O3, GaN, and Si substrates by non-catalytic, template-free conventional metal-organic vapor phase epitaxy (MOVPE) and hydride-metal-organic vapor phase epitaxy (H-MOVPE). The controlled growth of seed-sourced III-Nitride nanostructured materials has been demonstrated. Complex chemical equilibrium calculations were performed for the In-Ci-H-N system considering possible reactions to determine optimum conditions for InN NR formation. It was studied thermodynamically and confirmed experimentally that InN NR growth by H-MOVPE occurs at the growth-etch transition region. Dislocation free high quality InGaN nanorods with [001] growth axis were deposited via solid-vapor (SV) growth mechanism. Growth parameters and optimal growth conditions were determined. Ongoing efforts in our research on InN NRs foundational applications will be presented.

9:45 AM

LL5, AlN Nanowire Growth by Self-Patterning on SiC Substrates: G. Reza Yazdri; Mikael Syvajarvi; Rostkka Yakimova; Linkoping University

Self-patterned aligned AlN nanowires with diameter and length about 100 nm and 90 μm, respectively were grown on 4H-SiC substrate by physical vapor transport method. AlN hexagonal pyramids (HPs) were found to be nucleation sites for the evolution of the observed morphological forms. We study size reduction and limitation by choosing proper thermodynamical parameters, and converted AlN micro size crystals to the nano size. We will report different steps of AlN hexagonal hillocks formation and their evolution to HPs, on which nanowires were grown. Some nanowire properties like bending of AlN nanowires during scanning by scanning electron microscopy (SEM) will be also reported. By using optical microscopy, SEM, and atomic force microscopy we have studied the mechanism of the nanowire formation and piezoelectricity effect. Hot KOH etching confirmed that the self-patterning is initiated by dislocation etch pits in the SiC substrates.

10:00 AM

LL6, Late News

10:15 AM

LL7, Late News

10:30 AM Break

Session MM: Defects and Structural Characterization

Friday AM  Room: 314/315  Location: MGM Grand Hotel Conference Center

8:30 AM Invited

MM1, Atom Probe Reveals the Structure of InGaN Quantum Wells in 3D: Mark Galtrey; Rachel Oliver; Menno Kappers; Diane Zhu; Clifford McAleese; Colin Humphreys; David Larson; Peter Clifton; Alfred Cerezo; University of Cambridge; Imago Scientific Instruments; University of Oxford

We have examined InGaN-based quantum well (QW) structures with the Local Electrode Atom Probe (LEAP), which gives a field of view of 150nm with direct chemical information and sub-nanometre spatial resolution in three-dimensions. We show that InGaN with a range of compositions is a
random alloy, and so conclude that nm-scale In rich clusters are not essential for luminescence. We characterise the QW interfaces, and find that the upper interfaces of blue- and green-emitting QWs are more diffuse and rougher than the lower, with the difference in roughness providing a viable carrier localisation mechanism. Finally we examine a high-efficiency UV-emitting sample in which In in the barriers at the 0.1% level was thought to improve performance. However, we found In in the barriers of all our samples and so suggest that the observed discontinuities in the QWs at a ~50nm length scale are more important to performance.

9:00 AM
MM2, Effect of the Internal Electrostatic Potential on the Light Emitting Properties of InGaN Quantum Wells in Green LED; Zhizhao Wu1; A. Fischer; F. Ponce; W. Lee1; J. Ryoo; J. Limb; D. Yoo2; R. Dupuis2; 1Arizona State University; 2Georgia Institute of Technology
Variations in the piezoelectric field have been observed along the growth direction in InGaN-based diodes emitting in the green region. The internal electrostatic potential distribution across the active region consisting of five InGaN quantum wells has been determined by electron holography in a transmission electron microscope. The strength of the piezoelectric field decreases along the growth direction. Its effect on light emission has been evaluated by depth profiling cathodoluminescence, where the emissions from two peaks become increasingly distinct with increasing excitation voltage. The drop in piezoelectric field strength is proposed to be related to the neutralization of piezoelectric charges by hydrogen ions which are initially abundant in the p-region and diffuse into the quantum wells during thermal annealing.

9:15 AM
MM3, GaInN Light Emitting Diodes with Lattice-Matched AlInN/GaN Distributed Bragg Reflector on Si; Hiroyasu Ishikawa; Takashi Jimbo1; Takashi Egawa; 1Nagoya Institute of Technology
We report the impact of insertion of lattice-matched AlInN/GaN distributed Bragg reflector (DBR) on GaInN light emitting diodes (LEDs) on Si substrates. A series of the AlInN/GaN DBR LEDs with different pairs (0 to 14.5) were grown on 2-inch n-Si (111) substrates using a conventional horizontal metalorganic chemical vapor deposition method. The lattice matched AlInN/GaN DBR is superior to previous AlGaN/AIN DBR with respect to suppression of cracking, although the cracking density increases with the increase of DBR pairs. Cross sectional SEM images show that interfaces between AlInN and GaN are smoother than those of previous AlGaN/AIN DBR. The light output power of the LED with 14.5 pairs of DBR is about 3.6-fold larger than that of LEDs without DBR. Thus, the lattice-matched AlInN/GaN DBR is effective in enhancement of performance of GaInN LEDs on Si.

9:30 AM
MM4, V-Defect Analysis in Green and Deep Green Light Emitting Diode Structures; Mingwei Zhai; Shi You; Yuxin Wang1; Yong Xia1; Wei Zhao1; Yufeng Li1; Jayantha Senawiratne1; Zhizhao Zhang; Theeradetch Detchprohm1; Christian Wetzel1; 1Rensselaer Polytechnic Institute
V-defects in the active region of GaInN/GaN light emitting diodes (LEDs) have been considered to enhance light extraction and device efficiency. For 535 - 565 nm green and deep green LEDs on c-plane sapphire, we correlate the structural morphology with electroluminescence performance. Two classes of material with active region roughness of 5 nm and 0.6 nm (RMS) are analyzed in transmission electron microscopy. In the rough material, a high density of edge-type dislocations is identified that originates within the quantum wells (QWs). They initiate V-defects that exhibit [10-11] growth facets with a second set of narrow QWs and barriers. As V-defects widen with progressive growth, the width of QW and barriers on the c-plane increases. In the smooth material, however, no V-defects can be found. QWs and barriers are highly uniform and homogenous throughout the structure. LED emission is more uniform as well and output power more than doubles.

10:00 AM
MM6, Analysis of Basel Plane Stacking Fault Contribution to X-Ray Rocking Curve Widths in Non-Polar GaN; Mel McLaurin1; Asako Hirai1; Fung Wu1; Shuji Nakamura1; James Speck2; 1University of California, Santa Barbara
Non-polar and semi-polar orientated hetero-epitaxial films of the wurtzite nitrides typically exhibit large anisotropies in X-ray rocking curve widths. Though typically used for measurements of crystal mosaic, rocking curves are also sensitive to broadening of reciprocal lattice points due to small crystal coherence lengths. We present the relationship between a predominant feature of the microstructure of non-polar and semi-polar films, basal plane stacking faults, and the anisotropic X-ray rocking curve. A variant of the Williamson–Hall analysis is used to separate the component of X-ray peak broadening due to tilt mosaic from the broadening resulting from finite coherence length in m-plane oriented GaN films. Lateral broadening of the on-axis X-ray peak due to the presence of stacking faults is found to be the dominant source of the on-axis X-ray rocking curve anisotropy in the m-plane GaN films. Implications for measurements of other orientations of the wurtzite nitrides will be discussed.

10:15 AM
MM7, White X-Ray Microdiffraction Analysis of Defects, Strain and Tilts in a Free Standing GaN Film; R. Barabash1; G. Iee2; B. Haskell1; Shuji Nakamura1; James Speck2; 1Oak Ridge National Laboratory; 2University of California at Santa Barbara
We present a novel polychromatic microdiffraction (PXM) analysis of defects, strains and tilts in a free standing m-plane GaN film grown via hydride vapor phase epitaxy. The GaN film was initially grown upon a (100) gamma-LiAlO2 substrate, which spontaneously separated from the film upon cooling from the 900C growth temperature. The Li concentration 2 μm from each surface according to SIMS depth profiling, was sharply different at 5x1017 atoms/cc (back side) and 1x1011 (epi-surface) on the two faces. Comparable oxygen doping was observed on both surfaces. Because the high-energy x-ray beam passes through the GaN film the information is obtained from the thickness of the film. PXM indicated that the lattice parameter changes more than 2% with the depth of the film. The PXM results show that the film rotates 2-3 degrees through of the film thickness. The rotations are accompanied by film buckling.

10:30 AM Break
Technical Program

Session NN:
Molecular Beam Epitaxy of Nitride Semiconductors

Friday AM
Room:  312/317
September 21, 2007
Location: MGM Grand Hotel Conference Center

11:00 AM
NN1, Telecom Range Intersubband Transitions in GaN/AIN Multiple Quantum Wells Grown by Ammonia Molecular Beam Epitaxy: Sylvain Nicolay\(^1\); Amélie Dassaigne\(^1\); Laurent Nevou\(^1\); François. H. Julien\(^2\); Nicolas Grandjean\(^3\); \(^1\)École Polytechnique fédérale de Lausanne; \(^2\)Action OptoGaN, IEF, Université Paris-Sud

In this work, ammonia molecular beam epitaxy (NH3-MBE) is used to achieve GaN/AIN multiple quantum wells (MQWs) operating in the Telecom range. With this aim, it is necessary to use well thickness lower than 2 nm. As a consequence, the intersubband transition (ISBT) energy is very sensitive to the QW potential shape profile. Thus, diffusion and/or surface segregation phenomena that might occur at the MQW interfaces could be critical. In order to investigate this question, several samples were fabricated with different growth temperatures (Tgrowth) for AlN barriers. It is found that increasing Tgrowth leads to an increase of the ISBT energy, which is consistent with a more abrupt potential profile. Interestingly, further decrease of the temperature does not lead to higher ISB absorption energy whereas the maximum experimental value (~0.7 eV) is much below the theoretical one. This will be discussed on the basis of strain induced interface stability.

11:15 AM
NN2, Improved Growth Mode Diagram for Plasma–Assisted MBE Growth of (0001) GaN: Gregor Kohlbuehler\(^1\); Sergio Fernandez-Garrido\(^2\); Enrique Calleja\(^1\); James Speck\(^1\); \(^1\)University of California, Santa Barbara; \(^2\)Telecommunication

Based on real-time monitoring of the crystal growth modes during the PAMBE growth of (0001) GaN, we established a universal GaN growth diagram for growth temperatures to well above 800°C. Growth mode transitions from three-dimensional islanding to two-dimensional layer-by-layer and to step-flow growth were found with increasing Ga/N ratio. The latter transition coincided with a critical Ga adlayer coverage of 1 ML on the GaN surface, corresponding to a Ga/N ratio-dependent activation energy of ~1.5 eV. Unlike growth at low temperatures, N-rich growth conditions at very high growth temperatures were shown to follow an unexpected layer-by-layer growth mode (by the observation of RHEED intensity oscillations) while simultaneously effectively suppressing thermal decomposition. Finally, the growth modes were confirmed by atomic force microscopy of homoepitaxial GaN island nucleation studies, including correlations between surface diffusion and surface vicinity.

11:30 AM
NN3, Closed-Loop MBE Growth of Droplet-Free GaN with Very Metal Rich Conditions Using Metal Modulated Epitaxy with Mg and In: Shawn Burnham\(^1\); William Doolittle\(^1\); \(^1\)Georgia Institute of Technology

Improvements to the Metal Modulated Epitaxy (MME) technique using real-time feedback for closed-loop MBE growth will be introduced, and the use of Mg to examine the effects of Mg and In during droplet-regime GaN growth will be demonstrated. Improvements to the MME technique are achieved through computer controlled shutter transitions based on feedback from RHEED transients, thus creating a closed-loop control system for MBE. This allows the efficient buildup and depletion of the metal bilayer, which improves surface morphology and growth rate compared to the standard MME technique. RMS surface roughness was reduced by 41% by using this “Smart Shuttering” improvement to MME. A substantially higher peak concentration of Mg, approaching 10% atomic concentration, was achieved using the MME technique when growing thin Mg doped GaN layers. However, a negligible amount of In was incorporated into the very Ga-rich films, and increasing the In flux resulted in no appreciable change.

11:45 AM
NN4, Plasma-Assisted MBE Growth of (11-22)-Oriented GaN/AlN Quantum Wells on m-Sapphire: Lise Lahourcade\(^1\); Julien Renard\(^1\); Edith Bellet-Amalric\(^1\); Marie-Pierre Chauvat\(^1\); Pierre Ruterana\(^2\); Eva Monroy\(^2\); \(^1\)CEA-Grenoble; \(^2\)ENSICAEN

Polarization effects in III-nitrides can be reduced by growing along semipolar crystallographic axis. In this work we report on molecular-beam epitaxy of (11-22)-oriented AlN, GaN and GaN/AlN multi-quantum-well (MQW) structures on (11-100) m-sapphire. In a first approach, we have optimized the growth conditions of AlN. N-rich conditions and high substrate temperature make it possible to isolate the (11-22) orientation and to achieve two-dimensional AlN(11-22) layers. GaN deposited directly on m-sapphire results in (11-22)-oriented layers with (1-103)-oriented inclusions. An AlN(11-22) buffer is necessary to impose the (11-22)-orientation for the subsequent GaN layer. Best surface morphology is achieved under AlN-rich conditions, with a Ga excess of one monolayer on the GaN(11-22) surface. Applying the optimum growth conditions for two-dimensional AlN and GaN, we have synthesized GaN/AlN MQW structures. The structural quality is supported by x-ray diffraction, and the internal electric field attenuation is confirmed by the reduction of the luminescence Stark-shift.

12:00 PM
NN5, Growth of Nonpolar Cubic GaN/AIN Multiple Quantum Wells with Intersubband Transitions for 1.5 μm Applications: Donut Avs: Jörg Schörmann\(^1\); Klaus Lischka\(^2\); Eric DeCuir, Jr.\(^3\); M.O. Manasreh\(^4\); \(^1\)University of Paderborn; \(^2\)University of Arkansas

Cubic GaN/AIN short-period multiple quantum well structures were grown at 720°C by plasma-assisted molecular beam epitaxy on free standing 3C-SiC substrates. The samples consist of 100 nm thick GaN buffer and 20 periods of GaN/AIN active regions. The thickness of the AlN barrier is 1.35 nm for all samples, while the thickness of the GaN well varies between 1.6 nm-2.10 nm depending on the samples. The periodicity of the GaN/AIN active regions was confirmed by the presence of several peaks in the high resolution x-ray diffraction (HRXRD) spectra. The thickness of the total period was estimated by fitting the HRXRD data using a dynamic scattering theory. Furthermore, the room temperature optical absorption spectra of the intersubband transitions were obtained using a Bruker IFS-125HR spectrometer. The peak position wavelengths of these transitions were observed in the spectral region of 1.5–2.0 μm and confirmed theoretically by using a self-consistent Poisson-Schrödinger model.

12:15 PM
NN6, Molecular Dynamics of Ga Adlayers on GaN(0001): Jared Rinehimer\(^1\); Michael Widom\(^1\); Randall Feenstra\(^1\); \(^1\)Carnegie Mellon University

Molecular dynamics employing an embedded atom potential has been performed in an effort to deduce a structural model for the Ga adlayer(s) on GaN(0001) that agrees with low-energy electron diffraction data for this surface. Employing the same 4/3 monolayer Ga adlayer coverage as in the laterally-contracted bilayer model of Northrup et al. (PRB 61, 9932 (2000)), we use large surface unit cells (6400 atoms in the adlayer and 4800 in the substrate) with the adatoms placed initially at random surface sites. Energetically optimal structures are determined by simulated annealing and quenching. We find an optimal structure with a nearly 6x6 unit cell, having a diffraction pattern in good agreement with the experiment. As the simulation temperature is increased the adlayer is found to melt, again yielding a diffraction pattern in agreement with experiment, and at higher temperature a stable arrangement containing a fractional coverage of the adlayer is found.
This paper describes the properties and applications of GaN nanowires fabricated by MOCVD using regular MOCVD precursors with no additional catalysts. Nanowires can be grown on (0001) sapphire or SiC substrates and on (111) silicon. Arrays of GaN nanowires of arbitrary length can be fabricated and the position, orientation, diameter and length of each nanowire is precisely controlled. The paper will discuss the crystallographic, optical and electrical characterization of these nanowires, all of which indicate high quality GaN. Stimulated emission has been observed in optically pumped arrays and in single nanowires as short as 4.8 micrometres. The paper will also discuss preliminary heterojunction results and report our progress towards electrically pumped photonic devices. This scalable GaN nanowire process promises not only to develop revolutionary new photonic and electronic devices but also to move GaN nanowires from their current status as a laboratory curiosity into the commercial sector.

11:45 AM

O05, Maskless Epitaxial Overgrowth of GaN Nanocolumns: Kent Averett1; Joseph Van Nostrand1; John Albrecht3; Chi-Hung Yang1; 1Air Force Research Laboratory; 2National Taiwan University

GaN nanocolumns (NC), demonstrating excellent crystalline quality, have been grown by molecular beam epitaxy on both silicon (111) and sapphire (0001) substrates. The growth parameters for NC formation and density variation will be presented. An examination of photoluminescence characteristics show the columnar structures to be strain free. Additionally, SEM and TEM analysis has been performed showing the unique characteristics of each growth pattern vs. substrate, as well as confirmation of the absence of threading dislocations in the columnar structures. Epitaxial overgrowth of GaN nanocolumns has been successfully performed, by molecular beam epitaxy, showing lateral growth mode characteristics without the use of a mask, such as silicon dioxide or silicon nitride. Photoluminescence, Hall effect, and high resolution x-ray diffraction measurements demonstrate improved material quality over direct growth on sapphire. Transmission electron microscopy measurements examine the dislocation density of the overgrown material, and the results will be presented.

12:00 PM

O06, Growth and Optical Properties of Si- and Mg-Doped GaN Nanorods: Florian Furtmayr1; Martin Viemeyer1; Martin Stutzmann2; Martin Eickhoff2; 1Technische Universität München

Self assembled GaN nanorods were fabricated by plasma assisted molecular beam epitaxy on Si(111) substrates without the use of additional catalysts. The impact of both Si- and Mg-impurities on the growth kinetics and the optical properties has been investigated. Photoluminescence measurements were performed in the temperature range of 4K to 100K. Emission from free and donor bound excitons is dominant for undoped samples, whereas the contribution of donor-acceptor recombination increases with increasing doping concentrations. In weakly Mg-doped samples emission from the acceptor bound exciton was observed. The relation between luminescence characteristics, nanorod morphology, the degree of nanorod coalescence, and the incorporation of impurities is discussed.
Technical Program

Session PP:
MOVPE Growth of InGaN Alloys for Optoelectronics

Friday AM
September 21, 2007
Location: MGM Grand Hotel Conference Center

11:00 AM

PP1, Direct Observation of Uniform Optical Properties from Microphotoluminescence Mapping of InGaN Quantum Wells Grown on Slightly Misoriented GaN Substrates: Koichi Tachibana; Hajime Nago; Shin-ya Nuno; Toshiba Corporation

To realize high-performance InGaN-based laser diodes, it is very important to grow InGaN quantum wells with high crystalline quality. We have demonstrated extremely smooth surface morphology of GaN-based layers on slightly misoriented GaN (0001) substrates toward <1-100> direction. In this paper, we clearly demonstrate uniform optical properties of InGaN quantum wells on GaN substrates with misorientation toward <1-100> direction, using microphotoluminescence mapping. InGaN quantum wells were grown on some GaN (0001) substrates with misorientation angles from 0.0 to 0.4 degrees toward <1-100> direction. Microphotoluminescence mapping was investigated at room temperature. The fluctuation of peak wavelength and full width at half maximum in microphotoluminescence mapping was very small in the samples grown on GaN substrates with misorientation angles over 0.2 degrees. The average of full width at half maximum was as small as 55 meV when the misorientation angle was between 0.2 and 0.3 degrees.

11:15 AM

PP2, Morphology Evolution of InGaN Multi-Quantum Well Structures: Daniel Koleske; Stephen Lee; Gerald Thaler; Mary Crawford; Michael Coltrin; Sandia National Laboratories

The surface morphology evolution of InGaN multi quantum wells (MQWs) was studied as the number of QWs was increased. The MQW structures were grown using MOCVD and the InGaN QWs contained 20% indium as verified by x-ray diffraction. Single step heights were observed after the growth of an initial low temperature GaN barrier layer. After the growth of the first QW, however, we observed that the steps bunch due to the presence of indium during growth. As additional QWs are grown, only multiple step heights are observed. After the second QW growth a trench-hillock morphology develops that is oriented parallel to the step bunching direction. After 10 MQWs, the trench-hillock height difference approaches 30 Å which is the QW thickness. Neither the step bunching nor the trench-hillock morphology appears to be correlated to dislocations or V-type defects, suggesting that the step bunching drives the trench-hillock morphology evolution.

11:30 AM

PP3, Temperature Stability Studies of InGaN Thin Films and Multi-Quantum Well Structures: Gerald Thaler; Daniel Koleske; Stephen Lee; Mary Crawford; Sandia National Laboratories

As the indium content is increased in InGaN quantum wells (QWs) or thin films, the maximum growth temperature that these higher indium content InGaN alloys can withstand without decomposition is dramatically reduced. Subsequent growth of GaN capping or p-type layers must be performed at reduced temperatures to maintain InGaN QW integrity. While this is a well known feature of these InGaN films, the precise thermal budget is not well documented nor the mechanisms for InGaN degradation well understood. In this study, InGaN multi-QWs and thin films have been grown using MOCVD over indium compositions of 5 to 20% and capped with GaN. After growth, each of the InGaN films was annealed under flowing N2 in the MOCVD reactor to determine the kinetics of InGaN decomposition and the maximum temperature that each composition can withstand before degrading. Changes in the InGaN compositional structural integrity will be studied using x-ray diffraction.

11:45 AM

PP4, Growth of Periodic Microtip InGaN-Based LED Structure on Wet-Etch Patterned Sapphire Substrate: Hee Yun Kim; Tran Viet Cuong; Hyung Gu Kim; Hung Seob Cheong; Jae Young Park; Yong Seok Lee; Chang-Hee Hong; Eun-Kyung Suh; Semiconductor Physics Research Center

In this work, periodic microtip light-emitting diode structure was grown on wet-etch patterned sapphire substrate (PSS) by metal organic chemical vapor deposition. A pyramid shape of the PSS on SiO2 mask was initially fabricated by simple wet etching process. Experimental result revealed that the size as height and/or depth of pyramid shape strongly depend on the wet-etching time. After the etching process, honeycomb shape of GaN was grown on the PSS as follow: Firstly, the GaN was vertically grown on the horizontal c-plane of the PSS. After that, the horizontal c-plane of the GaN almost vanished and the honeycomb shape were formed on the inclined R-plane, where the density and distribution of the honeycomb shape could be controlled by the lateral growth mechanism of the GaN template. Our results demonstrated that under proper growth condition, periodic microtip LED structure could be fabricated on the honeycomb shape of GaN template.

12:00 PM

PP5, Enhancement of Indium Incorporation in InGaN Layer through Use of a “Bedding” Layer: Haryono Hartono; Chew Beng Soh; Soo Jin Chua; Eugene Fitzgerald; Singapore-MIT Alliance, National University of Singapore; Institute of Materials Research and Engineering; Singapore-MIT Alliance, Massachusetts Institute of Technology

Incorporation of Indium in GaN is a compromise between quality and high Indium content as a high growth temperature is good for quality but not the latter, and vice versa. We have found a growth method to increase Indium incorporation at the same growth parameters by preparing a composite “bedding” layer consisting of InGaN and InN layers. The InGaN layers, grown at 750°C, became approximately 75 nm is grown over it at a temperature of 580°C. A subsequent InGaN layer is grown over the InN layer under the same condition as the first. The photoluminescence of the top InGaN layer, emitting with the same intensity, is now shifted by 50 nm to 485 nm and broadened with FWHM of 75 nm.

12:15 PM

PP6, Growth of InGaN Optoelectronic Structures on 150 mm Sapphire Wafers in a Planetary Reactor®: C. Sommerhalter; B. Schoettler; B. Schineller; R. Schreiner; J. Kaeppeler; P. Flaks; P. Droste; M. Heuken; AIXTRON Inc.; AIXTRON AG; CrystalQ B.V.

One way of increasing the throughput of MOCVD to achieve cost targets for white lighting is by increasing the wafer size. The AIX 2800G4 HT MOCVD mass production tool is capable of growing either in the 42x2 inch or the 6x6 inch (150 mm) configuration. To assess the performance of the epitaxy tool five period InGaN/GaN multi-quantum-well structures on a ~3.5 μm thick GaN(Si) buffer layer were grown. The optimization of the growth was performed on 2 inch wafers in the 42x2 inch configuration. After optimization the reactor was reconfigured to the 6x6 inch configuration by exchanging the satellite disks. The photoluminescence mapping showed a mean wavelength of 450 nm with a standard deviation of 2.48 nm without edge exclusion. The total thickness of all layers was 3.555 μm with a thickness standard deviation below 1.1% without edge exclusion. Additional results such as morphology and crystal quality will be presented.
Session QQ: Special LEDs
Friday PM
September 21, 2007
Room: 313/314/315/316
Location: MGM Grand Hotel Conference Center
Program to be announced.

Closing Ceremony
Friday PM
September 21, 2007
Room: 313/314/315/316
Location: MGM Grand Hotel Conference Center