ISSLED 2008

International Symposium on Semiconductor Light Emitting Devices

April 27-May 2, 2008
Hyatt Regency Phoenix
Phoenix, Arizona

Advancing wide bandgap semiconductor science and technologies

FINAL PROGRAM

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The Magazine of Solid-State Lighting

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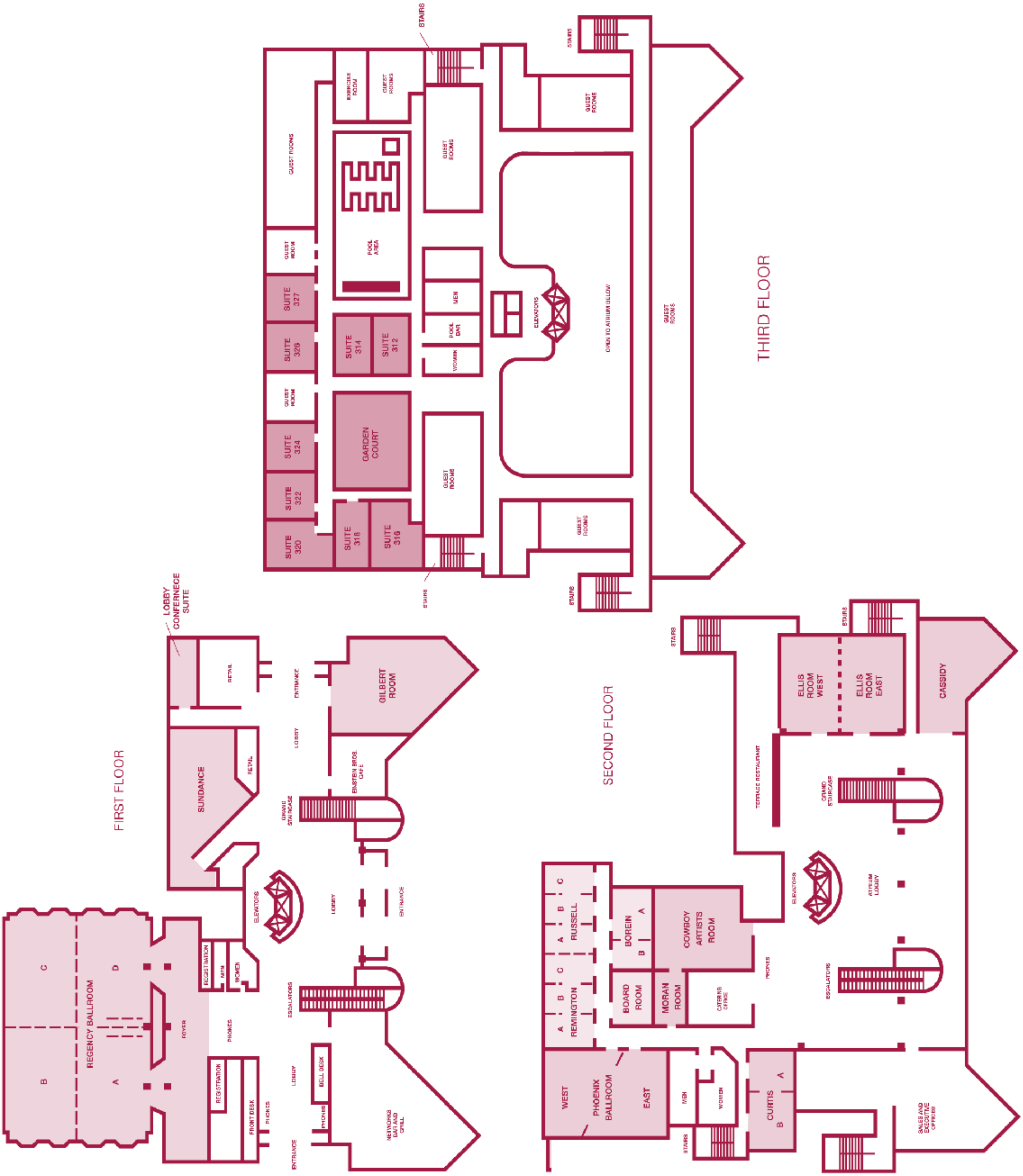
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POOL BAR
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Monday, April 28, 2008

Tuesday, April 29, 2008

Wednesday, April 30, 2008

Thursday, May 1, 2008

Friday, May 2, 2008

MONDAY AM

Plenary Session

Monday AM — Room: Regency Ballroom B
April 28, 2008 — Location: Hyatt Regency Phoenix

8:30 AM Opening Remarks

8:45 AM Plenary Talk

Session A: Photonic Crystal LEDs

Monday AM — Room: Regency Ballroom B
April 28, 2008 — Location: Hyatt Regency Phoenix

9:30 AM Invited

A1, Enhanced Efficiency of GaN-Based Vertical Light-Emitting Diodes with Photonic Crystal Patterns: *Hyun Kyong Cho*[1]; Sun-Kyung Kim[1]; Jeong Soo Lee[1]; Yong-Hee Lee[2]; [1]LG Electronics Institute of Technology/LED R&D Laboratory; [2]Korea Advanced Institute of Science and Technology/ Department of Physics

Photonic crystal (PhC) patterns were integrated onto an n-GaN surface to improve the light output from n-side-up GaN light-emitting diodes (LEDs) after laser lift-off (LLO) of the sapphire substrate. The PhC patterns, which had a lattice constant of 1,200 nm, were formed on top of the n-GaN surface through conventional photolithography (λ = 405 nm). The Si-gel-encapsulated n-side-up LED with PhC patterns (a = 1,200 nm), which had a depth of 500 nm, demonstrated up to 76% improvement in light output power at a forward current of 60 mA, compared with the planar-surface n-side-up LED. It is believed that photonic crystal (PhC) structure, as a waveguide and optical cavity, was very efficient in extracting light from the n-side-up LED and emitting it into the outer medium.

10:00 AM

A2, Enhancement of Light Extraction in GaN LEDs Using Photonic Crystals and Index Guiding Layers: *Kelly McGroddy*[1]; Aurelien David[1]; Elison Matioli[1]; Michael Iza[1]; Shuji Nakamura[1]; Claude Weisbuch[2]; Evelyn Hu[1]; [1]University of California, Santa Barbara, Materials Department; [2]Laboratoire Charles Fabry de l'Institut d'Optique

GaN has become the prominent material for blue-green light emitting diodes (LEDs). This work seeks to address current limitations in extraction efficiency of GaN LEDs by realizing the importance of an integrated optimization of the LED design by using both 2D photonic crystals in-plane and index guiding layers in the vertical direction to controllably emit most of the LED light into specific guided modes which can be efficiently extracted by the PC. The effects of variations in these critical components on the emission properties are measured experimentally. Angular-resolved electroluminescence clearly shows the ability to tailor the emission profile with the periodicity of the photonic crystal lattice. The intricacies and importance of vertical design are demonstrated. Increases in vertical emission as high as 4.5x are reported. Furthermore, the enhancements from PC light extraction will be directly compared to those achieved by surface roughening.

10:15 AM

A3, Photonic Crystal Light-Emitting Diode Fabricated with the Combination of Photoelectrochemical Wet Etching and Phase Mask Interference: Cheng-Hung Lin[1]; Cheng-Yen Chen[1]; Dong-Ming Yeh[1]; Chih-Feng Lu[1]; Chi-Feng Huang[1]; *C. C. Yang*[1]; [1]National Taiwan University

Light extraction from an InGaN/GaN quantum-well light-emitting diode (LED) has become an important issue for increasing the external quantum efficiency. We report a new method for generating 1-D and 2-D grating structures on the surface of an LED based on the photoelectrochemical (PEC) etching process. In this process, semiconductor is immersed in a conductive electrolyte within a container, which includes an optical window to allow the sample to be illuminated by a UV light. In LED fabrication, the surface of the epitaxial sample is etched to form grating patterns with the PEC method by exposing the sample under the UV light illumination, which passes through a phase mask to create the grating pattern. By rotating the sample by 90 degrees for another exposure, a 2-D grating can be generated. This method for fabricating the grating structures on LEDs is simple, inexpensive, and suitable for mass production.

10:30 AM Break

Session B: Visible LEDs I

Monday AM — Room: Regency Ballroom B
April 28, 2008 — Location: Hyatt Regency Phoenix

10:45 AM Invited

B1, The Fabrication of High Brightness Vertical Light Emitting Diodes by Chemical Lift-off Process: *Jun Seok Ha*[1]; S.W. Lee[1]; H.J. Lee[1]; H.-J. Lee[1]; S.H. Lee[1]; T. Kato[1]; Katsushi Fujii[1]; M.W. Cho[1]; T. Yao[1]; [1]Tohoku University

We report the first achievement of the fabrication of high-brightness vertical light-emitting diodes by chemical lift-off method. The chemical lift-off means detaching GaN LEDs from sapphire substrate by selective etching process. For this process, we introduced novel metallic buffer layer, CrN, which is etched out selectively by optimum chemical solution. In the view point of crystal growth, wurtzite GaN layer, RS-CrN layer and corundum c-sapphire showed a good agreement maintaining the epitaxial relationship of GaN<10-10>//CrN<12-1>//Al_2O_3<11-20>, GaN<11-20>//CrN<10-1>//Al_2O_3<10-10>. Vertical light emitting diodes were successfully fabricated by this process and they had similar device performances to those by laser lift-off method. Fabricated LEDs showed good current-voltage performance with low series resistance of 0.65Ω and low operating voltage of 3.11 V at 350mA. Also, these devices could be operated at a much higher injection forward current(1118mA at 3.70V) by thermally conductive metal substrate which enabled the high current operation with excellent heat dissipation.

11:15 AM

B2, Phosphor Free White Light from InGaN Blue and Green Light-Emitting Diode Chips Covered with Semiconductor-Conversion AlGaInP Epilayer: *Ray-Hua Horng*[1]; Pin Han[1]; Dong-Sing Wuu[1]; [1]National Chung Hsing University

A phosphor free white lamp was fabricated using the InGaN-based blue and green light light-emitting diode (LED) chips covered with semiconductor-conversion layer AlGaInP. The lamp can provide three bands: a 460 nm blue emission coming from the blue LED, a 555 nm green emission coming from the green LED and 630 nm red emission coming from the excited AlGaInP epilayer. As the white lamp was injected into 50 mA at room temperature, the chromaticity coordinates and correlated color temperature (TC) are (0.338, 0.335) and 5348 K, respectively. By separately injection current into blue and green LED chips, TC of lamp can be tuned from about 4000 to 5400 K.

11:30 AM

B3, Laser-Doped SiC Substrate-Based Single-Chip White Light-Emitting Diodes with Improved Color Temperature and Enhanced Power Output: Sachin Bet[1]; Nathaniel Quick[2]; *Aravinda Kar*[1]; [1]University of Central Florida; [2]Inflect Semiconductor, LC

This work demonstrates the fabrication of white light-emitting (LED) diodes in SiC substrates of both 4H-SiC and 6H-SiC polytypes using laser doping process. Inspite of being an indirect bandap semiconductor, SiC is potentially an excellent source for white LED based on the donor acceptor pair (DAP) recombination mechanism. Laser-doped Cr and Al behave as acceptors in SiC while N behaves as a donor. The DAP mechanism has been used for luminescence to tailor the color rendering capability of these LEDs. As opposed to the existing epilayer-based multilayer semiconductors which emit different colors to form pure white light, the SiC device is an LED embedded in a single chip, a ~ 450 micron thick SiC substrate, which emits pure white light. The general color rendering index for the SiC-based LEDs is in the range of 85-97%. The color temperature is tunable from cool white to warm white ranging from 2000-9500 K.

11:45 AM

B4, Characterizations of the Epitaxially Laterally Overgrown GaN Films on Europium-Silicate Thin-Film Phosphors: *Eun Hong Kim*[1]; Y. C. Shin[1]; D. H. Kim[1]; C. M. Kim[1]; B. G. Lee[1]; S. J. Leem[1]; J. H. Baek[2]; T. Jung[2]; S. J. Lee[2]; T. G. Kim[1]; [1]Korea University; [2]The Korean Photonics Technology Institute

Color rendering of white light-emitting diodes (LEDs) is an important factor that should be considered as a light source, which can be improved by having broadband spectra distributed throughout the visible region. To increase the color rendering index of the white light, we propose an idea of embedding thin-film phosphor into the GaN LED structures.In this work, the ELO of GaN was done on patterned thin-film phosphor and characterized by photoluminescence (PL), double crystal x-ray diffraction (DCXRD) and secondary electron microscopy (SEM). Layer structures of the Eu_2O_3/Si/pre-nucleated GaN/Sapphire were deposited by rf-sputtering and subsequently annealed at 1000 ~ 1100°C. The PL peaks of europium-silicate thin films were observed at 560 nm (FWHM of 100 nm). The ELO of GaN was done on the patterned thin film phosphor of pre-nucleated GaN/Sapphire by metal organic chemical vapor deposition. The structure of GaN/ELO was investigated by DCXRD and SEM.

12:00 PM

B5, Development of Phosphor Coatings for Efficient White LEDs: *Alexander Yunovich*[1]; Rasim Jabbarov[2]; Nahida Musayeva[2]; Ferdinand Scholz[3]; Thomas Wunderer[3]; Andrey Turkin[1]; Stanislav Shirokov[1]; [1]M.V. Lomonosov Moscow State University; [2]Institute of Physics, National Academy of Sciences of Azerbaijan; [3]Ulm University, Institut für Optoelektronik

A combination of InGaN/GaN LEDs ($\lambda \approx 395$ - 420 nm) with two coating phosphors ($SrGa_2S_4:Eu^{2+}$ and $SrS:Eu^{2+}$) was used to develop white LEDs with improved color rendering index. $SrGa_2S_4:Eu^{2+}$ has a broad excitation band at 370-460 nm leading to a strong emission at $\lambda \approx 537$ nm. The second phosphor, $SrS:Eu^{2+}$ shows a broad excitation spectrum. Therefore, it can be efficiently excited both at short wavelengths around 405 nm and at 537 nm, both leading to a strong emission at 615 nm. Hence, the emission of the first phosphor can be used to enhance the excitation of the second phosphor resulting in a fully optimized white color emitting LED by adjusting the concentrations of both phosphors which changes the ratio of green to red emitting bands. Possibilities to enhance efficiency of these white LEDs will be also discussed.

12:15 PM

B6, Micro-Patterned Graded-Refractive-Index Coatings of Co-Sputtered TiO_2 and SiO_2 for Enhanced Light-Extraction from GaInN Light-Emitting Diodes: *Frank Mont*[1]; David Poxson[1]; Martin Schubert[1]; Sameer Chhajed[1]; Ahmed Noemaun[1]; Jong Kyu Kim[1]; E. Fred Schubert[1]; Arthur Fischer[2]; Mary Crawford[2]; [1]The Future Chips Constellation, Rensselaer Polytechnic Institute; [2]Semiconductor Material and Device Sciences, Sandia National Laboratories

Semiconductor materials used for light-emitting diodes (LEDs) have large refractive indices (n = 2.5 to 3.5) in contrast to air (n = 1.0), resulting in total internal reflection losses and high Fresnel reflection losses at the refractive-index boundary thereby limiting light-extraction. Frequently, single-layer anti-reflection (AR) coatings are used in optical devices to minimize reflection at only a single angle and wavelength. Broad-band omni-directional AR characteristics are attainable by grading the refractive index of the AR coating from the substrate index to the ambient index. By micro-patterning graded-refractive-index AR coatings, deposited by reactive RF magnetron co-sputtering of $(TiO_2)_x(SiO_2)_{1-x}$ or $(ITO)_x(SiO_2)_{1-x}$, on top of GaInN LEDs, light-extraction is enhanced by 5% and 7%, respectively. Micro-patterning of ITO on ITO/GaN shows an enhancement of 20% for a pattern period of 4 μm. Three-dimensional ray-tracing simulations for micro-patterned graded-refractive index AR coatings on GaInN LEDs predict a light-extraction enhancement of 63%.

12:30 PM

B7, Metal Reflector Effects and Spherical Package Design in Light-Extraction Enhancement of InGaN-Based Light-Emitting Diodes: *Hisashi Masui*[1]; Natalie Fellows[1]; Hitoshi Sato[1]; Hirokuni Asamizu[1]; Shuji Nakamura[1]; Steven DenBaars[1]; [1]University of California, Santa Barbara

Effects of metal reflectors on radiant flux of InGaN-based light-emitting diodes (LEDs) were studied. Metal reflectors are commonly placed on the backside of LED dies. The present experimental approach of the suspended LED technique compared radiant flux directly with/without a reflector. LED dies with an evaporated Ag reflector had only 30% of the radiant flux as compared to LEDs without reflector. LED dies with Ag-paste reflector had 55% of the radiant flux of LEDs without reflector. To enhance light extraction, a spherical package was fabricated around a suspended LED die without reflector. The spherical package increased light extraction by a factor of 2.3. Light extraction of the sphere design was calculated. The sphere package does not require a point-like light source as far as light extraction is concerned due to the fact that a finite critical angle at the sphere/air interface exists according to Snell's law.

Session C: Visible LEDs II

Monday PM — Room: Regency Ballroom B
April 28, 2008 — Location: Hyatt Regency Phoenix

2:00 PM

C1, Improvement of Light Extraction from GaN-Based Thin-Film Light Emitting Diodes with Patterned Bottom Reflectors: *Kui Bao*[1]; Bei Zhang[1]; Tao Dai[1]; XiangNing Kang[1]; YongJian Sun[1]; GuiJun Lian[1]; Qiang Fu[1]; GuoYi Zhang[1]; Yong Chen[1]; [1]Peking University

To improve the light extraction of GaN based LEDs, we fabricated two kinds of GaN based thin-film LEDs having patterned bottom reflectors, with either the patterned bottom of un-doped GaN (u-GaN) or the patterned polymer on reflective layer, respectively. The former is made by ultraviolet (UV) imprinting a two-dimensional (2D) micron-array on the sapphire backplane and then delivering the micro-pattern onto the u-GaN layer by a modified laser lift-off (M-LLO) technique. The latter is made by UV-imprinting 2D micro-pattern onto the UV curable polymer layer over the LLO un-doped GaN surface. Deposition of silver layer and bonding on silicon submount were done afterwards. The light extraction from both LEDs was improved compared with the conventional one. The detailed comparison and simulation were presented and discussed in this report. This work is supported by 863 program (2006AA03A113),973 program (2007CB307004) and NSF (60276034, 60577030 and 60607003) of China.

2:15 PM

C2, Efficiency Enhancement of InGaN/GaN Light-Emitting Diodes by Wet-Etched Patterned Sapphire Substrates: *Chih-Ling Wu*[1]; Ming-Hsin Lo[1]; Yun-Li Li[1]; [1]National Taiwan University

For last few years, there have been lots of progresses on InGaN/GaN-based light-emitting diodes (LEDs). Many new applications based on these LEDs have been developed owing to the merits of LEDs, such as high-brightness, long-lifetime and high stability. However, for future illumination applications, it is very important to further enhance the external quantum efficiency of LED. In this research, InGaN/GaN light-emitting diodes were fabricated with wet-etched patterned sapphire substrates. Different geometrical patterned sapphire substrate is manufactured with different etching conditions. InGaN/GaN LEDs with multiple-quantum-well (MQW) structure are grown on these patterned sapphire substrates. As-grown samples with different patterned substrates are characterized with low temperature and room temperature photoluminescence (PL) for relative internal quantum efficiency. The enhancement of extraction efficiency is also evaluated by the simulations of TracePro. Finally, the electrical and optical characteristic of the InGaN/GaN LED with optimized patterned sapphire substrates will be further discussed.

2:30 PM

C3, GaN Based Light Emitting Diode Fabricated on Micro-Lens Patterned Sapphire Substrate: *Tae Su Oh*[1]; Yong Seok Lee[1]; Hyun Jeong[1]; Eun-Kyung Suh[1]; [1]Chonbuk National University

GaN based light-emitting diodes were fabricated on micro-lens patterned sapphire substrate (ML-PSS). ML patterning on sapphire substrate was performed by using photolithography with photo-resist reflow and dry etching process using inductively coupled plasma. The ML-PSS was prepared using a periodic micro lens pattern with diameters of 3 µm and spacing of 2, 4, and 5 µm, respectively, on sapphire substrate. The leakage current of the LEDs fabricated on the ML-PSS greatly decreased compared to that of a conventional LED and it decreases with increasing ML pattern spacing; it decreases from 1.8 µA to 0.2 µA at reverse voltage of 15 V as the ML pattern spacing is increases from 2 µm to 5 µm. The output power of the LED with 5 µm spacing was 155 % higher than that of a conventional LED and 15 % higher than that of the LED on the PSS with 2 µm spacing.

2:45 PM

C4, Revolutionary Method for Increasing the Efficiency of White Light Quantum Dot LEDs: *Chad Duty*[1]; Ron Ott[1]; Adrian Sabau[1]; Gerald Jellison[1]; Keith Leonard[1]; Curt Maxey[1]; Steve Allison[1]; Biswajit Das[2]; Theodore Moustakas[3]; [1]Oak Ridge National Laboratory; [2]University of Nevada, Las Vegas; [3]Boston University

Covering a light-emitting diode (LED) with quantum dots (QDs) can produce a broad spectrum of white light. However, current techniques for applying QDs to LEDs suffer from a high density of defects and a non-uniform distribution of QDs, which respectively diminish the efficiency and quality of emitted light. Oak Ridge National Laboratory has the unique capability to thermally anneal QD structures at extremely high power densities for very short durations. This process, called pulsed thermal processing (PTP), reduces the number of point defects while maintaining the size and shape of the original QD nanostructure. Therefore, the efficiency of the QD wavelength conversion layer is improved without altering the emission spectrum defined by the size distribution of the quantum dot nanoparticles. The current research uses PTP to anneal various QD systems on passive (quartz) and active (LED) substrates and measure the resulting increase in photoluminescent efficiency.

3:00 PM

C5, Multicolored Light Emission from InGaN/GaN Multiple Quantum Wells Growth on Pyramid Facets of Epitaxial Lateral Overgrown GaN: A Novel Way to Fabricate White Light Emitting Diodes on Epitaxial Lateral Overgrown GaN: *In-Hwan Lee*[1]; Jin-Woo Ju[1]; Lee-Woon Jang[1]; Ju-Won Jeon[1]; Jin Soo Kim[1]; Seung-Jae Lee[2]; Jong Hyeob Baek[2]; [1]Chonbuk National University; [2]Korea Photonics Technology Institute

InGaN/GaN MQW were successfully grown on the inclined GaN {1-101} microfacets. Conventional photolithography and subsequent growth of GaN were employed to generate the V-shaped microfacets along <11-20> direction. The well-developed microfacets observed by SEM and the clear HRXRD results indicated that the MQW was successfully grown on the GaN 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 416 nm to 491 nm as the probing points were changed along upward direction. Photoluminescence (PL) peak wavelength was increased by increasing the mask width in the merged samples. On the other hand, PL peak wavelength was decreased in spite of larger mask width in the non-merged microfacet. Present works thus propose a novel route to fabricate a monolithic white light emitting diode without phosphors by growing the InGaN/GaN MQWs on {1-101} facet

3:15 PM

C6, Highly-Diffractive, Plasma Damage-Free Photonic Crystal for Vertical Injection GaN Slab LED: *Sun-Kyung Kim*[1]; Kyung-Keun Park[1]; Hyun-Kyong Cho[1]; Junho Jang[1]; Yong-Hee Lee[2]; [1]LG Electronics Institute of Technology; [2]Korea Advanced Institute of Science and Technology

We report highly-diffractive, TiO_2-patterned photonic crystal for vertical injection GaN slab LEDs. In the GaN slab LED, a thermally-conductive thick supporter (Cu) is substituted for an initial sapphire substrate by a laser lift-off process. The effective dissipation of unwanted heat from the GaN slab LED results in alleviating the efficiency droop at high injection current. Additionally, the metal supporter makes current path vertical for the uniform injection into active medium. However, the GaN slab LED eliminates light escape route through the side sapphire facets. Thus, it requires the extraction structure to convert guided slab modes into leaky continuum ones. In this study, we incorporate a square-lattice hole array into a transparent, high refractive index (n=2.7) thin (230nm) TiO_2 layer, deposited onto the top surface of the GaN LED. The integrated output power of TiO_2-patterned LEDs is enhanced by a factor of ~1.5 in comparison to those of flat surface LEDs.

3:30 PM Break

Session D: Visible LEDs III

Monday PM — Room: Regency Ballroom B
April 28, 2008 — Location: Hyatt Regency Phoenix

3:45 PM Invited

D1, Characterization of Onemonolayer-Thick InN QWs in GaN Matrix and Their Application for Light-Emitting Devices: *Songbek Che*[1]; Tetsuji Fujimoto[1]; Hideyuki Saito[1]; Naoki Hashimoto[1]; Akitaka Hikida[1]; Kazuaki Matsui[1]; Eunsook Hwang[1]; Xinqiang Wang[2]; Yoshihiro Ishitani[1]; Akihiko Yoshikawa[1]; [1]Chiba University; [2]InN-Project as a CREST-Program of JST

Extremely thin InN QW (about 1 monolayer (ML)) is a good candidate for a new active layer of high efficiency laser diodes in UV-blue to green region. We fabricated 1 ML InN/GaN 5-QWs under different growth temperatures by RF-MBE and MOCVD. It was found that precise control of monolayer-thick InN well (fractional ML to more than 1 ML) could be achieved by RF-MBE growth and transition energies of 1 ML and 1.5 ML InN QWs were determined to be about 3.2 and 2.95 eV. Moreover, by using the InN/GaN 5-QW as an active layer, high efficiency LEDs were successfully fabricated by MOCVD. We confirmed a small blue shift (about 3 nm) in the EL spectra of the LED (l=445 nm) under the different current density. This result indicates the improvement of internal quantum efficiency by reducing QCSE in the very thin InN well active layer.

4:15 PM

D2, Optoelectrical Properties of Dual Wavelength GaN Based Light-Emitting Diode: *Hao Fang*[1]; Liwen Sang[1]; Zhijian Yang[1]; Guoyi Zhang[1]; [1]Peking University

In this work, the optoelectrical properties of dual wavelength GaN based LED were studied. The dual wavelength LED was grown by metal organic vapor phase epitaxy. Then, the samples were fabricated into 350×350 μm^2 LED chips and packaged with epoxy resin. The optoelectrical properties of the samples were measured. The output power was 0.77 mW at 20 mA, and 1.24mW at 50 mA, respectively. The EL spectra were measured at different forward voltages. The two emission lines were 430 nm and 510 nm. As the forward voltage increase, the intensities of the two peaks become stronger. The ratio of the integrated intensity of the two emission lines maximized when the forward voltage was 4.5 V. The large current region ln(I)-V curve could also be divided by 4.5 V by linear fit the two parts of the curve separately. This phenomenon was attributed to the change of carrier transport mechanism.

4:30 PM

D3, P-Active Region InGaN Blue Light Emitting Diodes with Improved Performance at High Driving Currents: *Dmitri A. Zakheim*[1]; Dmitri A. Bauman[2]; Maxim G. Agapov[2]; [1]Ioffe Institute; [2]Epi-Center

In this paper we report on successful fabrication of InGaN-based blue light-emitting diode (LED) heterostructures with active region located on p-side of p-n junction. In such structures the radiative recombination efficiency in active region is controlled by electron injection rather than hole injection in standard heterostructures. Since n-AlGaN layer blocks hole leakage more effectively than p-AlGaN blocks electron leakage, the p-active region LEDs demonstrate superior external quantum efficiency (EQE) at high driving currents compared to standard ones. The on-wafer EQE of standard MOCVD grown LED chips with 0.14 mm2 area reaches maximum (13.8%) at about 5 mA and constitutes ~9% at 100 mA. The similar p-active region LED chips demonstrate the same maximum efficiency at 5 mA, while their EQE at 100 mA is ~11%. In pulsed operation, the difference between EQE vs. pumping curves of standard and p-active region LEDs is even more pronounced.

4:45 PM

D4, Spectral Analysis with High-Speed Thermal Measurements of High Power Diode Arrays: *Nicholas Rada*[1]; Gregory Triplett[1]; Samuel Graham[2]; Scott Kovaleski[1]; [1]University of Missouri - Columbia; [2]Georgia Institute of Technology

As the proliferation of LED technology accelerates and optoelectronic device feature size continues to decrease to several nanometers, thermal issues continue to impact device performance and reliability. High power LED's are of particular importance because of their promise of highly efficient replacements for incandescent devices in general lighting applications; however, an array of such devices generates considerable heat, which must be considered. Accurate determination of die temperature is of critical importance for thermal management and remains a technical barrier. This study builds on previous work utilizing high speed thermography to examine die temperature, self heating effects, and power loads by incorporating spectral analysis to examine device behavior. Through the study of spectral characteristics including frequency shifting and luminous power output, it is proposed that die temperature and detrimental self-heating effects can be determined so that device and system level decisions regarding thermal management including packaging evaluation can be made.

5:00 PM

D5, Thermomechanical Analysis of Chip-on-Board Packaging of LEDs: *Samuel Graham*[1]; Minseok Ha[1]; [1]Georgia Institute of Technology

Chip-on-Board (COB) is a very attractive technology for packaging power LEDs which can lead improved thermal performance and reliability. Substrates for COB packaging include insulated metal substrates (IMS), ceramics, and direct bonded copper (DBC). While all are effective in addressing LED thermal management, they can lead to vastly different thermomechancial responses in the packaged structure. In this work, we present a numerical analysis of COB LED packages. The junction temperature and mechanical response of 1W, 3W, and 5W LEDs as well as multichip modules were analyzed based on packaging architecture and convective heat transfer coefficient. Comparisons between structures are used to discuss the role of packaging materials on the thermomechanical response of power LEDs. Finally, a new thermally conductive and mechanically compliant structure which can be used to attach die to metal substrates will be presented. Its improvement in performance over solder die attach materials will be discussed.

5:15 PM

D6, Enhancement of Light Extraction in III-Nitride Light Emitting Diode Employing Photonic Crystal Structure: *Young Chul Shin*[1]; E. H. Kim[1]; C. M. Kim[1]; B. G. Lee[1]; Y. Zhong[1]; J.-M. Park[2]; W. Lung[2]; K.-M. Ho[2]; J. H. Baek[3]; T. Jung[3]; T. G. Kim[1]; [1]Korea University; [2]Iowa State University; [3]The Korean Photonics Technology Institute

There is still a great need for improving the light-extraction efficiency of GaN-based light-emitting diodes (LEDs), because the high refractive index of GaN (n=2.46) prohibits light beyond a critical angle from being extracted due to Fresnel reflection. Thus, photonic crystal (PC) assisted light extraction is a promising method for ultra-high efficient LEDs. In this work, we report the enhancement of light extraction in two dimensional (2D) PC GaN LEDs, in which both indium-tin-oxide (ITO) and p-GaN layers were patterned on a nanosize scale using two-beam laser interference and reactive ion etching. The PCs in-cluded both hole and pillar structures, with crystal lattices from 460 to 920nm and holes depth from 12 to 26nm, respectively. Details on the performance of 2D PC GaN LEDs will be presented at the conference.

NOTES

Session E: Non-Polar LEDs I

Tuesday AM
April 29, 2008

Room: Regency Ballroom B
Location: Hyatt Regency Phoenix

8:30 AM Invited

E1, MOCVD Growth of $Al_xGa_yIn_{1-x-y}N$ MQW Structures on Non-Polar Bulk GaN Substrates: *Balakrishnan Krishnan*[1]; Bin Zhang[1]; Lachab Mohamed[1]; Qhalid Fareed[1]; Vinod Adivarahan[1]; Asif Khan[1]; [1]University of South Carolina

A key problem in the growth of $Al_xGa_yIn_{1-x-y}N$ on non-polar bulk a- and m-plane GaN is the generation of stacking faults leading to a featured surface morphology. We present a systematic study of low-pressure MOCVD growth and characterization of GaN, $In_xGa_{1-x}N$/ $In_yGa_{1-y}N$ and $Al_xGa_{1-x}N$/ $Al_yGa_{1-y}N$ multiple-quantum-wells on non-polar GaN. Increased V/III ratio (as high as 60,000) was found to be the key for obtaining high-quality stacking fault free featureless growths with RMS indices of 0.1-0.3 nm. TEM analysis indicated extremely sharp growth interfaces and absence of stacking faults. The MQW structures exhibited strong edge and surface stimulated emissions at wavelengths ranging from 420 nm to 340 nm. To the best of our knowledge this is the first report of optically pumped non-polar lasing in the deep UV part of the spectrum. In this paper details of growth, structural and PL and EL characterization will be presented.

9:00 AM Invited

E2, Structural and Optical Properties of Non-Polar GaN Thin Films: *Zhihao Wu*[1]; Alec Fischer[1]; Fernando Ponce[1]; Barbara Bastek[2]; Jurgen Christen[2]; Tim Wernicke[3]; Michael Kneissl[3]; Markus Weyers[3]; [1]Arizona State University; [2]University of Magdeburg; [3]Ferdinand-Braun-Institut für Höchstfrequenztechnik

The structural and optical properties of GaN thin films grown in the direction have been correlated using transmission electron microscopy and cathodoluminescence spectroscopy. The GaN film was grown on an r-plane sapphire substrate, and epitaxial lateral overgrowth was achieved using SiO_2 masks. A comparison between the properties of GaN directly grown on sapphire and GaN grown laterally over the SiO_2 mask is presented. The densities and dimensions of the stacking faults vary significantly, with a high density of short faults on the window region, and a much lower density of longer faults in the wing region. The luminescence spectra consist of peaks at 3.465 and 3.41 eV, corresponding to emission from donor-bound excitons and basal-plane stacking faults, respectively. A correlation between the structural defects and the emission peaks is presented.

9:30 AM

E3, Growth of Non-Polar GaN on High Temperature AlN Buffers on r-Plane Sapphire by MOVPE: *Fabio Ranalli*[1]; [1]University of Sheffield

There is an increasing demand to grow III-nitrides on non-polar and semi-polar substrates as both piezo-electric and spontaneous polarization induced strong internal electric field can be minimized. However, it is extremely difficult to achieve non/semi-polar III-nitrides with high crystal quality on a sapphire substrate. Recently, our high temperature AlN buffer approach with no nucleation layers, which was originally developed for the growth of high quality GaN films on c-plane sapphire, has been successfully applied for the growth of non-polar GaN on r-plane sapphire, different from the most widely used approach. The non-polar GaN with a high quality has been confirmed by high resolution XRD. A mirror like surface has been achieved, confirmed by optical microscopy. Further experiments including PL, TEM and AFM are being carried out.

9:45 AM

E4, Improved Quality of a-Plane GaN Grown with Flow-Rate Modulation Epitaxy on r-Plane Sapphire Substrate: Jeng-Jie Huang[1]; Tsung-Yi Tang[1]; Chi-Feng Huang[1]; *C. C. Yang*[1]; [1]National Taiwan University

We use the flow-rate modulation epitaxy (FME) technique to improve the crystal quality of a pit-free a-plane GaN (11-20)film grown on r-plane sapphire (1-102) substrate. With the FME technique, the width of the rocking curve in X-ray diffraction measurement is significantly reduced. Also, the surface roughness in either atomic-force-microscopy scanning or surface profiling is decreased. Here, the FME technique means to alternatively turn on and off the supply of Ga atoms while N atoms are continuously supplied without changing the flow rate. Under the used growth conditions, the optimized FME parameters include the on/off periods at 10/10 sec. During the period of closing the flow of TMGa, the continuous supply of nitrogen can lead to the formation of stoichiometry structure under the high-Ga growth condition, which is required for pit-free growth. During this period, Ga atoms can further migrate to result in a flatter surface.

10:00 AM

E5, The Influence of V/III Ratio on the Strain in Nonpolar a-Plane GaN Film Grown by MOCVD: *Lubing Zhao*[1]; Tongjun Yu[1]; Jiejun Wu[1]; Zhijian Yang[1]; Xurong Zhou[1]; Guoyi Zhang[1]; [1]Peking University

Nonpolar a-plane (11-20) GaN films had been grown on r-plane (1-102) sapphire substrates by metal organic chemical vapor deposition. The influences of V/III ratio on the strain in the a-plane GaN films were investigated. When V/III increased from 1000 to 6000, all the frequencies of A1(TO), E1(TO), and E2(high) modes were firstly red-shifted and then blue-shifted, and had a minimum at V/III=2000, which indicated that the in-plane compressive strain was least in this sample. XRD analysis showed a least tensile strain and narrowest FWHM of rocking curve in the V/III=2000 sample along (11-20) direction. However, the FWHM of the active phonon modes in Raman spectra had a maximum value at V/III=2000,which implied that the crystal quality was worst. The fact that FWHM of XRD rocking curve did not increase, means occurrence of more defects other than threading dislocations when strain released.

10:15 AM

E6, Late News

10:30 AM Break

Session F: Non-Polar LEDs II

Tuesday AM
April 29, 2008

Room: Regency Ballroom B
Location: Hyatt Regency Phoenix

10:45 AM Invited

F1, Characterization of Polarized Light Emission from Nonpolar Light-Emitting Diodes: *Hisashi Masui*[1]; Mathew Schmidt[1]; Natalie Fellows[1]; Hisashi Yamada[1]; Kenji Iso[1]; Shuji Nakamura[1]; Steven DenBaars[1]; [1]University of California, Santa Barbara

InGaN/GaN light-emitting diodes (LEDs) prepared on m plane were subjected to optical polarization characterization. An optical microscope in a confocal configuration with 20 μm depth of field was employed. Polarization ratios were 0.49 and 0.80 for 395- and 445-nm emitting devices. The splitting energy between the two polarizations was 10 meV for the former and was 50 meV for the latter; these results were attributed to the larger in-plane strain in the InGaN active layer of the 445-nm emitting LED structure. The m-plane LEDs were combined with a liquid-crystal display unit to demonstrate the potential as a polarized light source. An extinction ratio of 0.2 was obtained; this relatively high ratio was attributed to the primitive experimental setup.

11:15 AM

F2, InGaN Single Quantum Wells Grown on Semipolar and Nonpolar Bulk GaN Substrates Studied by Time-Resolved Photoluminescence: *Gregory Garrett*[1]; Hongen Shen[1]; Michael Wraback[1]; Anurag Tyagi[2]; Mathew Schmidt[2]; James Speck[2]; Steven DenBaars[2]; Shuji Nakamura[2]; [1]US Army Research Laboratory; [2]University of California, Santa Barbara

Single quantum wells (SQW) of low InN concentration InGaN grown on high quality nonpolar and semipolar substrates cut from bulk GaN boules are studied by time-resolved photoluminescence (PL) techniques. Data is taken at varying pump fluence and sample temperature to study radiative lifetimes, nonlinear non-radiative recombination, and carrier localization or separation. For a 16 nm SQW on *m*-plane GaN, a room-temperature lifetime of ~5.5 ns increases to 950 ps at higher pump fluences while at the same time the PL intensity, scaled by the incident pump power, becomes weaker. At 13 K, the dominant lifetime becomes a consistent ~450 ps while the rollover in the scaled PL persists. For an equivalent SQW grown on (11-22)-plane GaN, the same phenomenon is observed, but at higher pump fluence. Room-temperature lifetimes are found to vary from 50 ns, at low density, to 400 ps while low-temperature lifetimes are around 275 ps.

11:30 AM

F3, Recombination Dynamics of Free Excitons and Basal Plane Stacking Faults Emission in Coalesced a-Plane GaN ELO Structures Investigated by Spectrally and ps-Time-Resolved Cathodoluminescence Microscopy: *Barbara Bastek*[1]; Frank Bertram[1]; Juergen Christen[1]; Tim Wernicke[2]; Markus Weyers[2]; Michael Kneissl[3]; [1]Otto-von-Guericke-University Magdeburg; [2]Ferdinand-Braun-Institut für Höchstfrequenztechnik, Berlin; [3]Technical University Berlin and Ferdinand-Braun-Institut für Höchstfrequenztechnik, Berlin

A-plane GaN layers epitaxial lateral overgrown by MOVPE on [0110]-oriented stripe masks stripe masks on r-plane sapphire were characterized using ps-time-resolved cathodoluminescence (CL) microscopy at various temperatures. The initial lifetime of basal stacking fault (BSF) luminescence exponential decrease with rising temperature yielding an activation energy of 7 meV in good agreement with values for the valence band discontinuity at the BSF. In contrast, the free exciton (FX) decay shows a non monotonous temperature dependence. The initial lifetime of 180 ps at 5K is primarily given by the capture of FX by donors to form (D^0,X) as well as by BSFs. With rising temperature this capture process becomes less effective and the time constant decreases as $T^{-1/4}$ to a minimum of 104 ps at T = 60K. Above 60K, i.e. when FX starts to dominate the spectrum, the lifetime increases rapidly reaching a value of 240 ps at 300K.

11:45 AM

F4, Enhanced Performance of GaInN Based Green Light Emitting Diodes on Non-Polar GaN: *Theeradetch Detchprohm*[1]; Mingwei Zhu[1]; Yufeng Li[1]; Yong Xia[1]; Wei Zhao[1]; Jayantha Senawiratne[1]; Lianghong Liu[2]; Drew Hanser[2]; Christian Wetzel[1]; [1]Rensselaer Polytechnic Institute; [2]Kyma Technologies Inc.

We demonstrate the performance improvement of 520-540 nm GaInN based green light emitting diodes (LEDs) on non-polar GaN by implementing low threading dislocation density GaN bulk substrate. The growth of LEDs consisting of GaInN/GaN quantum wells on (11-20) GaN bulk substrate is found to exhibit better epitaxial layer quality and sharper interface -especially in the active region- than that of LEDs on (1-102) Al_2O_3 substrates. As judged from transmission electron microscopy results, these LED devices on bulk substrate replicate the quality of the GaN bulk substrate without any additional dislocations generated in the homoepitaxial layers. In the consequence, the electroluminescence performance reveals increased light output power as high as 3 fold with a narrow spectral line width when compared to a similar device of (11-20) GaN on (1-102) Al_2O_3. In addition, the device also manifests a rather small wavelength shift (less than 10 nm) as a function of drive current.

12:00 PM

F5, Visible LEDs Grown on c-Plane and a-Plane Free-Standing Substrates: *Russell Dupuis*[1]; Jianping Liu[1]; Jaehyun Ryou[1]; [1]Georgia Tech

Green LEDs with p-InGaN:Mg were grown on c-plane bulk GaN substrates. Compared to green LEDs grown on sahhire substrates, the pit density was tremendously reduced due to low density of dislocations present in the LED structures. As a result, the reverse leakage current was two orders of magnitude lower than that of green LEDs grown on sapphire substrate.To eliminate the internal field in the active region of green LEDs, the growth of LED structures were performed on a-plane bulk GaN substrates. LED epitaxial structures free of crystalline defects have been achieved. Although similar growth conditions as green LEDs grown on c-plane bulk GaN substrate were used except for the thickness of the QWs, the electroluminescence of the light emitting diodes exhibited peak wavelengths of ~450 nm. It was found that the emission wavelengths were independent of current level at low current densities before heating effects were observed.

12:15 PM

F6, Effects of the Buffer Layer Thickness on the Formation of Basal Plane Stacking Faults in a-Plane GaN Epilayer Grown on r-Sapphire: *Zhihao Wu*[1]; Alec Fischer[1]; Fernando Ponce[1]; Yoshiya Yokogawa[2]; Shunji Yoshida[2]; [1]Arizona State University; [2]Matsushita Electric Industrial Company, Ltd.

The thickness of the low temperature AlGaN buffer layer (LT-BL) grown on r-sapphire substrate has been found to directly affect the structure of LT-BL itself as well as the structural and optical properties of a-plane GaN subsequently grown. A thinner 30 nm LT-BL consists of randomly distributed grains with size of tens of nanometers while a thicker 90 nm LT-BL has a uniform and largely coalescenced crystalline structure with a consistent distribution of basal plane stacking faults (BSF) with extension length of tens of nanometers. The a-plane GaN grown on the thinner 30 nm LT-BL has less density and longer extension of BSF and thus stronger signature of donor bound exciton emission than that grown on the 90 nm LT-BL. The relationship of the formation and propagation of BSF to the nucleation of LT-BL has been discussed.

12:30 PM

F7, Late News

Session G: Non-Polar LEDs III

Tuesday PM Room: Regency Ballroom B
April 29, 2008 Location: Hyatt Regency Phoenix

2:00 PM Invited

G1, Built-in and External Bias-Induced Quantum-Confined Stark Effects in a Nonpolar m-Plane $In_{0.15}Ga_{0.85}N$/GaN Multiple Quantum Well Light-Emitting Diode: Takeyoshi Onuma[1]; Hiroaki Amaike[1]; Masashi Kubota[2]; Kuniyoshi Okamoto[3]; Hiroaki Ohta[3]; Junnichi Ichihara[3]; Hidemi Takasu[3]; *Shigefusa Chichibu*[1]; [1]Tohoku University; [2]University of Tsukuba; [3]Rohm Company, Ltd.

Quantum-confined Stark effects (QCSEs) in a polarization-free m-plane $In_{0.15}Ga_{0.85}N$/GaN MQW blue LED fabricated on the low defect density free-standing GaN substrate (Mitsubishi Chemical) were investigated by means of time-resolved photoluminescence (PL) measurement. The electroluminescence (EL) peak at 2.74 eV little shifted to the higher energy with the increase in current, because of the absence of the polarization fields. The effective radiative lifetime increased and the nonradiative lifetime decreased with the increase in the junction field, and the results were quantitatively explained in terms of field induced QCSE including tunneling escape of holes from the MQW. As a result of the use of the low defect density substrate, the equivalent internal quantum efficiency, which was approximated as the spectrally integrated EL intensity at 300 K divided by that at 150 K, of 43% was achieved.

2:30 PM

G2, Longitudinal and Transverse Piezoelectric Field of InGaN/GaN Heterostructure Grown on Polar, Semi-Polar and Non-Polar GaN Templates: *Qiyuan Wei*[1]; Zhihao Wu[1]; Ti Li[1]; Fernando Ponce[1]; [1]Arizona State University

In this paper the piezoelectric fields of the InGaN/GaN heterostructure grown on arbitrary (hkil) planes of GaN template are calculated. Both the direction and the magnitude of the longitudinal and transverse piezoelectric field are determined. For semi-polar planes, the longitudinal piezoelectric field reaches zero at 42 degree of polar angle while the transverse piezoelectric field reaches zero at 66 degree. For non-polar planes, the piezoelectric field only has the transverse components along the [0001] direction and its magnitude is less than half of the piezoelectric field for polar plane case. It is demonstrated that the polar angle at which the piezoelectric field diminish is insensitive to the indium composition and it is a feature of the InGaN/GaN system. The effect of the piezoelectric field on devices is also discussed.

2:45 PM

G3, Strain Effect on Polarized Optical Properties of c-Plane GaN and m-Plane GaN: Renchun Tao[1]; Tongjun Yu[1]; Chuanyu Jia[1]; Zhizhong Chen[1]; Zhixin Qin[1]; Guoyi Zhang[1]; [1]Peking University

InGaN/GaN (3 nm/10 nm, 10 periods) MQWs LED structures with different In compositions were grown on sapphire by MOCVD and the polarized spontaneous edge-emitting electroluminescence was measured. It was found that the polarization degree increased with wavelength. The longer wavelength corresponded to higher In composition and larger strain in the well regions of LEDs. An effective-mass Hamiltonian based on perturbation theory was applied to calculate the relative oscillator strength of the valence bands for c-plane GaN and m-plane GaN. The mechanism of strain effect on polarization properties in GaN was discussed. It is suggested the strain-induced strong changes of the oscillator strengths should be one of important physical origins of the light polarization in GaN-based materials. This work was supported by projects of Natural Science Foundation of China _Nos. 60676032, 60577030, and 60476028 and National Key Basic Research Special Foundation of China under Grant No. TG 2007CB307004.

3:00 PM Invited

G4, m-Plane InGaN/GaN Optoelectronic Structures on γ-$LiAlO_2$ Grown by MOVPE: H. Behmenburg[1]; T.C. Wen[2]; Y. Dikme[1]; C. Mauder[2]; L. Rahimzadeh Khoshroo[2]; M.C. Chou[3]; M.V. Rzheutskii[4]; E.V. Lutsenko[4]; G.P. Yablonskii[4]; J. Woitok[5]; H. Kalisch[2]; R.H. Jansen[2]; *M. Heuken*[1]; [1]Aixtron AG; [2]RWTH Aachen; [3]National Sun Yat-Sen University; [4]National Academy of Sciences of Belarus; [5]PANalytical B.V.

GaN growth on $LiAlO_2$ perpendicular to the m-plane is one possibility to deposit non-polar material. An in-situ nitridation as the first step is essential for the deposition of GaN in the m-plane mode. To prevent decomposition, the substrate was sealed with a thin InGaN:Mg layer. A 220 nm thick GaN:Mg and a 500 nm thick GaN layer complete the buffer structure. In 2Theta/Omega scans, only m-plane GaN was detected, and rocking curves of the symmetric (1-100) reflex revealed an improvement in quality with increasing thickness of the InGaN:Mg layer up to 100 nm. Above this thickness, the line width deteriorated from 750 to 1100 arcsec. The trend was verified by AFM measurements which showed a minimum surface roughness of 11.4 nm RMS. InGaN LED structures on such buffers showed photoluminescence wavelengths in the blue spectral range which were independent of excitation intensity and exhibited a high degree of polarization.

3:30 PM Break

Session H: Visible LEDs IV

Tuesday PM Room: Regency Ballroom B
April 29, 2008 Location: Hyatt Regency Phoenix

3:45 PM

H1, Study of the Efficiency Roll-off Behaviors of InGaN-Based Green, Blue and UV Light-Emitting Diodes: *Yi Yang*[1]; Xian-An Cao[1]; C. H. Yan[2]; [1]West Virginia University; [2]Lumei Optoelectronics

We studied the underlying mechanism for the efficiency roll-off problem of InGaN-based green, blue and UV multiple-quantum-well LEDs over a wide injection range. Thermal effects due to self-heating were minimized by pulsing the LEDs with a duty cycle of 0.1-2%. Both the QE and peak shift appears to be strongly dependent on the In content in the active region. The QE of the green LED peaks at a current density as low as 1.4A/cm2, and decreases dramatically as current is increased, whereas the UV-LED has a nearly constant QE at currents up to1kA/cm2. In contrast to minimal current-induced peak shift in the UV LED, a monotonic peak blueshift, of a total amount of ~110 meV, is seen for the green LED. These results offer a strong support for our argument that current overflow from localized states is the major nonthermal mechanism responsible for the efficiency rolloff in InGaN-based visible LEDs.

4:00 PM

H2, Investigation of Efficiency Droop Behavior for InGaN/GaN Light-Emitting Diodes: *Yu-Hung Lai*[1]; Yi-Ru Huang[1]; Yun-Li Li[1]; [1]National Taiwan University

In recent years, InGaN/GaN-based light-emitting diodes (LEDs) have attracted great interest for use in fields of commercial products, such as backlighting, signage, and solid state illumination. The so-called efficiency droop behavior is the reduction of LED's emitting efficiencies at higher current densities. In this research, to understand the efficiency droop phenomenon both experiment and simulation are performed. InGaN/GaN-based LEDs with various well thicknesses at active region are grown on c-plane sapphire substrates by metal organic chemical vapor deposition. Experiment results showed that thicker well structure behaves less efficiency droop, while thinner well structure has significant efficiency reduction at high current densities. It is assumed that Auger recombination as carrier concentration raised is the dominant mechanism for the reduction of efficiency. However, we propose that carrier overflow at higher current densities by simulation is another

TUESDAY PM

important mechanism for this phenomenon. The more optical characteristic in each structure will be further discussed.

4:15 PM

H3, Efficiency Droop in GaInN/GaN LEDs: The Effect of Dislocation Density, Physical Origin, and Possible Solution: *Martin Schubert*[1]; Sameer Chhajed[1]; Jong Kyu Kim[1]; E. Fred Schubert[1]; Min Ho Kim[2]; Dan Koleske[3]; Mary Crawford[3]; Stephen Lee[3]; Arthur Fischer[3]; Gerald Thaler[3]; Michael Banas[3]; Joachim Piprek[4]; [1]Rensselaer Polytechnic Institute; [2]RPI/Samsung Electro-Mechanics; [3]Sandia National Laboratories; [4]NUSOD Institute LLC

GaInN/GaN LED samples with low dislocation density, high peak efficiency and substantial efficiency droop are compared to samples with high dislocation density, low peak efficiency and reduced droop using a rate equation model. Analysis reveals that dislocations contribute to increased nonradiative recombination at lower currents and reduced peak efficiency. The higher-current nonradiative carrier loss mechanism that causes the efficiency droop is very similar as a function of current for the two samples, despite significant differences in carrier density; this is consistent with carrier leakage out of the MQW active region. We also describe simulations of LEDs with polarization-matched AlGaInN layers, which are proposed as a solution to the problem of efficiency droop. The simulations show that the polarization charges at the interfaces in the active region enable carrier leakage, and are thus the physical origin of efficiency droop. Experimental results of LEDs with AlGaInN/GaInN active regions are also discussed.

4:30 PM

H4, Evolution of Step Morphology in InGaN Films and Effect on Luminescence Properties: *Daniel Koleske*[1]; Gerald Thaler[1]; Stephen Lee[1]; Mary Crawford[1]; Michael Coltrin[1]; Karen Cross[1]; [1]Sandia National Laboratories

Recent studies suggest that InGaN QW thickness fluctuations, acting in conjunction with piezoelectric forces produce sufficient exciton localization to decrease non-radiative recombination at dislocations. The implications of this hypothesis make the study of InGaN step morphology and control of the InGaN/GaN interfaces potentially crucial for understanding and improving LED quantum efficiency. We have found that the GaN single-layer step morphology changes to multiple-layer steps during InGaN growth. The extent of this change depends on surface indium coverage during growth. For green emitting MQWs, AFM measurements show that the frequency of multiple-layer steps increases for samples containing one and two QWs compared to GaN, and for increasing numbers of QWs the step-height distribution remains constant. Improved InGaN/GaN interface smoothness is produced by higher GaN barrier growth temperatures as observed by the increased intensity of higher-order x-ray diffraction peaks. The origin and consequences of the InGaN step morphology changes will be presented.

4:45 PM

H5, $In_{0.1}Ga_{0.9}N$ Layers with Different Thickness: TEM, X-Ray and Photoluminescence Studies: *Zuzanna Liliental-Weber*[1]; M. Hawkridge[1]; S. Bedair[2]; A.E. Berman[2]; A. Emara[2]; J. Domagala[3]; J. Bak-Misiuk[3]; [1]Lawrence Berkeley National Laboratory; [2]North Carolina State University; [3]Institute of Physics Polish Academy of Sciences

InGaN is used as the active material in optical devices and gives the possibility of obtaining light emission with tunable wavelength, depending on In content. However, due to the large size difference between Ga and In atoms, growth of $In_xGa_{1-x}N$ is challenging. Here, we explore In distribution and the structural quality of $In_{0.1}Ga_{0.9}N$ layers varying from 100 nm to 1000 nm, thick, nominally. TEM, x-ray and photoluminescence methods were applied. Each layer (except the thinnest one) consisted of two sub-layers: strained and relaxed. Agreement between x-ray and TEM studies was achieved. Much lower In content was observed in the strained sub-layer than in the relaxed one. The thicker the layer, the more structural defects were observed. A shift of photoluminescence peaks toward longer wavelengths and multiple PL peaks were observed with increasing sample thickness, suggesting that structural defects influence In distribution and the position of PL peaks.

5:00 PM

H6, GaN:In Underlayer Induced V-Defects in Epitaxy of InGaN Multiple Quantum Wells: Weihua Chen[1]; *Hu Xiaodong*[1]; [1]Peking University

InGaN multiple-quantum-well structures deposited at an underlying GaN:In layer have been grown by metal-organic chemical-vapor deposition(MOCVD). Transmission electron microscopy (TEM) using two beam conditions with different diffraction vectors revealed that every threading dislocation (including screw edge mixed dislocation) can induce V-defects or inverted hexagonal pyramid defects from the GaN:In underlayer. The sidewalls of V-defect extend and cross the InGaN QW multiple InGaN/GaN quantum well region. In addition, the sidewalls extending across the QWs and terminating at the upper p-GaN layer also indicate that the In atoms assist the extending of the sidewalls of v-defects. HRTEM gave credible evidence that the phase separation of In atoms assists the generation and extending of V-defects. According to the result, an approach using multiple InxGa1-xN/GaN inter-layers to reduce the TD density was suggested.

5:15 PM

H7, Fabrication of MgZnO Films by Molecular Precursor Method and Its Application to UV-Transparent Electrodes: *Yoshihiro Mashiyama*[1]; Kaori Moshioka[1]; Shigetoshi Komiyama[1]; Mitsunobu Sato[1]; Tohru Honda[1]; [1]Kogakuin University

MgZnO thin films were fabricated by molecular precursor method (MPM) for the realization of low-cost near-ultraviolet (UV) transparent electrodes for GaN-based UV light-emitting diodes (LEDs). The MgZnO fabrication by MPM requires a common solvent for both Zn and the Mg precursor solutions. We found that an ammonia solution is one of the common solvents. MgZnO thin film was fabricated on the quartz glass substrate using the MgZnO precursor solution. The Mg composition in the films was estimated using the X-ray photoelectron spectroscopy (XPS). The solid phase composition of Mg in the film is 40-50% of its molar fraction in the liquid phase. The X-ray diffraction patterns indicate the films have a hexagonal single phase as same as ZnO. The possibility of MgZnO films for the application to UV transparent electrodes on GaN-based UV LEDs is discussed.

Session I: Visible LEDs V

Wednesday AM
April 30, 2008

Room: Regency Ballroom B
Location: Hyatt Regency Phoenix

8:30 AM Invited

I1, Benefits of Negative Polarization in *n*-InGaN/*p*-GaN Single Heterostructure Light Emitting Diode with *p*-Side Down: *Meredith Reed*[1]; Eric Readinger[1]; Craig Moe[1]; Hongen Shen[1]; Michael Wraback[1]; Alexander Syrkin[2]; Alexander Usikov[2]; O. Kovalenkov[2]; Vladimir Dmitriev[2]; [1]Army Research Laboratory; [2]Technologies and Devices International, Inc.

Effects of negative polarization charge at the *n*-InGaN/*p*-GaN interface on the performance of HVPE-deposited single heterostructure *n*-$In_{0.17}Ga_{0.83}N$/*p*-GaN LEDs with *p*-side down are investigated. This negative polarization charge at the interface leads to a reduced barrier for hole injection from *p*-GaN to *n*-InGaN, with a hole accumulation layer forming within the InGaN near the *n*-InGaN/*p*-GaN interface. Electrons encounter a significant barrier for injection from the *n*-InGaN into *p*-GaN, compounded by the heterobarrier, making *p*-GaN behave like an effective electron blocking layer. As a result, superlinear increase in light output as injection current increases below 20A/cm^2 and peak emission wavelength shift from 495nm to 470nm are observed. We show that the combination of 2D hole-gas formation on the *n*-InGaN side of the hetero-interface and enhancement of the electron barrier to transport across this interface may reduce efficiency droop at high current density without the need for an AlGaN electron blocking layer.

9:00 AM

I2, Junction Temperature Analysis and Temperature Dependent Quantum Efficiency in GaInN Based Green Light Emitting Diodes: *Jayantha Senawiratne*[1]; T. Detchprohm[1]; W. Zhao[1]; M. Zhu[1]; Y. Li[1]; Y. Xia[1]; C. Wetzel[1]; [1]Rensselaer Polytechnic Institute

The junction temperature of electrically and thermally heated green GaInN/GaN LEDs on sapphire and bulk GaN substrate was determined by photoluminescence (PL) spectroscopy up to 600 K (327°C).[1] Across the die, the temperature distribution was determined by cathodoluminescence mapping. We find elevated temperature near the p- and n- contacts and attribute it to limited current spreading and local Joule heating. Combining PL with electroluminescence (EL) spectroscopy, the efficiency and spectral performances of the LED dies was analyzed as a function of junction temperature. Both, EL peak position and external quantum efficiency behave very different under external thermal and internal electric heating. Such behavior is explained by the junction temperature and electric field dependent carrier dynamics in the quantum wells. [1]J. Senawiratne, W. Zhao, T. Detchprohm, A. Chatterjee, Y. Li, M. Zhu, Yong Xia, J. L. Plawsky, and C. Wetzel, Phys. Stat. Sol., Accepted.

9:15 AM

I3, MOCVD Growth and Stimulated Emission Study of InGaN Quantum Dots Grown Using a High Temperature AlN as Buffer: Q. Wang[1]; *Tao Wang*[1]; J. Bai[1]; A. G. Cullis[1]; P. Parbrook[1]; F. Ranalli[1]; [1]University of Sheffield

It is extremely difficult to achieve InGaN quantum dots with both high density and high crystal quality. Recently, we developed a so-called high temperature AlN buffer approach for growth of GaN on sapphire by MOCVD. Both TEM and XRD have confirmed that the dislocation density is significantly reduced, compared to the conventional GaN layer. Our InGaN QDs with an ultra-high density were grown on such high-quality GaN surface, and a stimulated emission with a low threshold has been observed at room temperature. The longest lasing wavelength from our InGaN QDs is ~450 nm, although the spontaneous emission is at ~530 nm. This is significantly different from InGaN-based quantum well structure. Further experiments are being carried out in order to understand the stimulated emission mechanism.

9:30 AM

I4, Emission Efficiency Performance of InGaN/GaN Multiple-Quantum-Well Light-Emitting Diodes with Various Si Doping Profiles in the Active Region: *Yi-Ru Huang*[1]; Yu-Hung Lai[1]; Yun-Li Li[1]; [1]National Taiwan University

III-nitride based high-brightness light-emitting diodes have attracted a lot of attention due to their various applications on displays, illumination and optical storage systems. Many efforts have been made to improve material quality, internal quantum efficiency. To further improve the device performance, it is important to enhance the internal quantum efficiency and the design of the epitaxial structure of the active region must be focused. According to previous studies, it was suggested that introducing Si-doping in the barrier layers improves the performance of InGaN/GaN multiple-quantum-well LEDs. In this research, InGaN/GaN MQWs LEDs with varied doping profiles of barriers in MQW structures are grown with MOCVD. As-grown samples are characterized with low temperature and room temperature photoluminescence for internal quantum efficiency. Electrical and optical properties of standard fabricated LED chips are measured. The simulation of the performance is also performed and compared to the experimental ones. The details will be further discussed.

9:45 AM

I5, Electroluminescence of Green and Blue GaInN/GaN Multiple Quantum Well Light Emitting Diodes under Photon Bias: *Yufeng Li*[1]; Jayantha Senawiratne[1]; Yong Xia[1]; Wei Zhao[1]; Mingwei Zhu[1]; Theeradetch Detchprohm[1]; Christian Wetzel[1]; [1]Future Chips Constellation, Rensselaer Polytechnic Institute

We observe that electroluminescence (EL) and I-V characteristics of GaInN/GaN green and blue light emitting diodes (LEDs) can be modulated under 325 nm and 408 nm photon bias. For example, a solar cell effect with variable open-circuit voltage is so observed. In all samples, EL can be greatly enhanced. While a 325 nm photon bias enhances EL at low forward bias, under 408 nm photon bias, the maximum EL enhancement in green LEDs is reached above the open-circuit voltage of the solar cell effect. This distinction cannot be seen in the blue LEDs. We propose that the EL enhancement is due to a photocarrier mediated enhanced carriers distribution across the quantum wells. The placement of photocarriers at various depths is found to explain the wavelength dependence of the EL enhancement. Moreover, a direct correlation of EL enhancement and external quantum efficiency of the samples is found.

10:00 AM

I6, InGaN/GaN LEDs MOCVD-Grown on Si(111) on Insulator: Correlation of Spatially Resolved Optical and Electrical Properties: Lars Reissmann[1]; Thomas Fey[1]; Armin Dadgar[1]; Frank Bertram[1]; S. Tripathy[2]; V.K.X. Lin[2]; S.L. Teo[2]; *Juergen Christen*[1]; Alois Krost[1]; [1]Otto-von-Guericke University; [2]Institute of Materials Research and Engineering

InGaN/GaN-based light emitting diodes (LEDs) were grown by MOCVD on (111)-oriented 6 inch nanoscale silicon-on-insulator (SOI) substrates. The buried oxide layer thickness of 150–160 nm combined with the 45 nm thick Si(111) overlayer gives highly reflective substrates. LEDs were investigated by scanning micro-photoluminescence (μ-PL), simultaneous laser beam induced current (LBIC) mapping and scanning micro-electroluminescence (μ-EL) spectroscopy under forward current of 50 mA. PL wavelength image exhibits blurry shapes of longer peak wavelengths compared to average. They can be attributed to local thickness and/or refractive index fluctuations. The LBIC signal shows preferential current paths through the device similarly to μ-EL but in reverse direction. Hence, surface defects/contaminations of the LED (dark spots) or p-contact metallization geometry (brigth border), can be distinguished from electrical properties of the bulk LED material. μ-EL shows grainy areas of lower injection current density. Highest current densitiy leads to blue shifted emission due to band filling.

10:15 AM

I7, Application of Narrow-Band Color Cathodoluminescence SEM-Mode to the Study of Defects in InGaN/AlGaN/GaN-Heterostructures: *Alexander Yunovich*[1]; Stanislav Shirokov[1]; Petr Ivannikov[1]; Pavel Miroshnikov[1]; Anton Gabelchenko[1]; Maksim Agapov[2]; Boris Yavich[2]; [1]M.V. Lomonosov Moscow State University; [2]JVC "Svetlana-Optoelectronics"

One of the effective methods for GaN structure characterization is use the SEM in the color cathodoluminescence (CCL) mode. The CCL system can operate with a standard RGB-set of optical filters for obtaining true color image. To improve spectral resolution we used a set of narrow band filters that have overlapped spectral characteristics with the maximal transparencies at the wavelengths: 420, 450 and 480 nm. This method was applied to study defects in InGaN/AlGaN/GaN LED structures grown by MOCVD-technique. A new method allowed visualizing spectral non-homogeneity of luminescence in quantum wells in some LEDs structures. For all specimens non-homogeneity of quantum efficiency was discovered, with the typical size of non-homogeneous field of 1-10 microns. Considerable spatial non-homogeneities of diffusion length in p-area were discovered by variation of beam accelerated voltage.

10:30 PM Break

Session J: Materials Growth and Characterization

Wednesday AM
April 30, 2008

Room: Regency Ballroom B
Location: Hyatt Regency Phoenix

10:45 AM Invited

J1, Metastable UV Luminescence in Mg-Doped GaN Layers Grown on Freestanding GaN Substrates: Galia Pozina[1]; *Bo Monemar*[1]; H. Amano[2]; I. Akasaki[2]; A. Usui[3]; [1]Linköping University; [2]Meijo University; [3]Furukawa Company, Ltd.

Metastability of near band gap UV emissions in high quality Mg-doped GaN layers grown by metal-organic vapor phase epitaxy on freestanding GaN substrates grown by halide vapor phase epitaxy has been studied by cathodoluminescence (CL) and photoluminescence (PL). CL or PL spectra change their initial shape within a few minutes under electron irradiation or UV laser excitation; however the details of temporal changes in PL and CL are different. The common feature for PL and CL is vanishing of the acceptor bound exciton (ABE) line within 30-60 min under excitation. Additionally, the emissions related to the stacking faults (SFs) amplify significantly in CL. No SF related emissions have been observed in PL. Annealing at 800°C in nitrogen atmosphere reduced metastable behavior of the UV luminescence. The temporal changes in PL and CL are permanent at low temperatures; however, the virgin spectra can be recovered after heating to room temperature.

11:15 AM

J2, Highly Spatially Resolved X-Ray Analysis of GaN Microdisc LEDs on Silicon: *A. Krost*[1]; J. Blaesing[1]; F. Bertram[1]; A. Franke[1]; A. Dadgar[1]; A. Diez[1]; V. K. X. Lin[2]; S. L. Teo[2]; J. Christen[1]; S. Tripathy[2]; [1]Otto-von-Guericke-Universitaet Magdeburg; [2]Institute of Materials Research and Engineering

GaN-based microdisc LEDs on silicon were fabricated by all dry processing techniques. The XeF2-based vapor etching of silicon was used to create flat-top mushroom-shaped LED structures. The resulting circular discs (diameters 300 – 500 µm) are freestanding, except for Si posts at the center. Due to the residual stress in the ~2.9 µm thick nitride film, the freestanding parts of the discs slightly bent downwards. We investigated strain and film bending by a new Bruker D8 HR/GADDS XRD system with rotating anode designed for fast, high spatially-resolved measurements. With this setup a spatial resolution >1 micrometer can be achieved. Using an area detector, such measurements on microdiscs can be performed by one XRD scan. With these measurements, the bending of the film can be analyzed and radii of curvature around 8 mm for 500 µm microdiscs are determined. We will discuss the XRD results and compare with optical measurements.

11:30 AM

J3, Raman Analysis and Luminescence Properties of InN Layers Grown by High-Pressure CVD: Ronny Kirste[1]; Jan-Hindrik Schulze[1]; Markus R.Wagner[1]; Mustafa Alevli[2]; *Axel Hoffmann*[1]; Nikolaus Dietz[2]; [1]TU Berlin; [2]Georgia State University

Improvements in the group III-nitride materials quality are crucial for many envisioned applications such as tunable emitters from the infrared to the ultraviolet wavelength regime, radiation hardened magneto/optoelectronics or high speed optoelectronic devices. At present, one of the limiting factors is the growth and integration of InN in indium-rich group III-nitride alloys by chemical vapor deposition (CVD) at growth conditions similar to those used for GaN. High-pressure CVD (HPCVD) has been established as a viable approach, enabling the growth of InN at temperatures of up to 850°C at reactor pressures around 15bar. We present Raman and temperature dependant photoluminescence (PL) measurements on InN layers grown by HPCVD. The Raman analysis of the strain sensitive E_2(high) mode revealed nearly unstrained layers with a FWHM of down to 8cm^{-1}, indicating a high crystal quality.PL analysis exposed emissions up to 1.45eV. A strong correlation between crystal quality and optical properties has been found.

11:45 AM

J4, Optical Microscopic Characterization of GaN/InGaN Micro-Disk LEDs on Silicon: Alexander Franke[1]; *J. Christen*[1]; F. Bertram[1]; A. Dadgar[2]; A. Krost[2]; K. X. Lin[3]; S. L. Teo[3]; S. Tripathy[3]; [1]Otto-von-Guericke University; [2]Otto-von-Guericke-University Magdeburg and AZZURRO Semiconductor AG, Magdeburg; [3]Institute of Material Research and Engineering, IMRE

We report on the optical, micro-photoluminescence (µ-PL) and cathodoluminescence (CL) characterization of MOVPE grown GaN-micro-disk LED structures on top of a silicon substrate with InGaN QWL active layers. Micro-PL mappings of the sample surface show statistical distribution of the GaN emission wavelength between 357.9 and 358.2 nm. A linescan across the whole diameter-range exhibits a peak-shift correspond to a tensile stress of about 0.37 GPa at the free-standing part of the disk. An abrupt decrease of stress is clearly observable where the GaN is in direct contact with underlying Si-stalk. Cross-sectional CL linescans from top to bottom of the disk exhibit increasing tensile stress at the Si stalk and decreasing tensile stress at free-standing area. The QWL emits homogeneously at 460.9 nm in the center part of the micro-disk and periodically with symmetric pattern of alternating 460.9 nm emission interrupted by a 466.1 nm emission on the free standing micro-disk-ring.

12:00 PM

J5, In Situ Measurement of the Raman Shift of the E2 Line in GaN as a Function of Applied Uniaxial and Biaxial Load: *Grady White*[1]; Lawrence Robins[1]; Albert Paul[1]; Hanmin Zhao[2]; [1]National Institute of Standards and Technology; [2]Lumileds

GaN films are important materials for applications ranging from wireless communications to solid state lighting. In these applications, the strain state of the films affects the final device properties: e.g., carrier mobility, output wavelength. Numerous groups have used Raman measurements to determine strain states in GaN films; however, the calibration of the strain-induced Raman peak shifts has been accomplished through the use of multiple film specimens that have been grown under varying conditions to generate a range of biaxial residual stress states. We report here the results of in situ micro-Raman measurements of GaN films that have subjected to either biaxial or uniaxial loading conditions. We observe a change in peak position with biaxial load of -2.97E-3, at the low end of the values reported in the literature. Our observed shift with uniaxial load is the same as that for the biaxial loading configuration.

12:15 PM

J6, Time-Resolved Cathodoluminescence Study on Mg Doped GaN: *Alec Fischer*[1]; Sridhar Srinivasan[1]; Fernando Ponce[1]; [1]Arizona State University

The optical properties of Mg-doped GaN films grown by MOCVD with Mg concentrations of the order of 10^{18} and 10^{19} cm^{-3} have been analyzed by cathodoluminescence at low temperatures (4.2 K). Low-temperature, time-resolved cathodoluminescence shows that the radiative recombination rate of the 3.27 eV donor-acceptor-pair increases with Mg concentration.

Luminescence during decay time shows that the 3.19 eV peak (formerly assigned to a longitudinal phonon replica) has a significantly different behavior than the 3.27 eV peak (donor-acceptor pair), strongly suggesting that the former is not a phonon replica of the latter or that there is a broad emission overlapping its intensity.

12:30 PM

J7, GaN-Based Microdisk LEDs on Nanoscale SOI(111) Substrates: S. Tripathy[1]; A. Dadgar[2]; V. K. X. Lin[1]; K. Y. Zang[1]; S. L. Teo[1]; T. E. Sale[1]; S. J. Chua[1]; A. Diez[2]; J. Bläsing[2]; J. Christen[2]; *A. Krost*[2]; [1]Institute of Materials Research and Engineering, A*STAR; [2]Otto-von-Guericke-Universitaet Magdeburg

InGaN/GaN light emitting diode (LED) structures are grown on (111)-oriented silicon-on-insulator (SOI) substrates using metal organic chemical vapor deposition. The SIMOX SOI with Si overlayer thickness of 50 and 100 nm are used as highly reflective substrates for GaN epitaxy. High-resolution x-ray diffraction, transmission electron microscopy, and micro-Raman spectroscopy have been used to characterize the structural quality of these LED structures. The circular microdisk patterns are created by multiple-mask photolithography, inductive coupled plasma etching of GaN, and lateral contact metallization. Due to the reflectivity changes at the bottom Si/SiO_2 interfaces beneath AlN buffer and light reflections at the Fabry-Perot boundaries, an increased electroluminescence is observed from these microdisk LEDs. A detailed reflectivity analysis has been carried out to model the EL lineshape of the LED structures on SOI. These microdisk LEDs on SOI may be suitable for wavelength stabilization and may reduce the blue shift at increasing injection currents.

NOTES

Session K: UV Materials and Light Emitters I

Thursday AM Room: Regency Ballroom B
May 1, 2008 Location: Hyatt Regency Phoenix

8:30 AM Invited
K1, 222-273 nm AlGaN Deep Ultraviolet Light-Emitting Diodes Fabricated on High-Quality AlN Buffer on Sapphire: *Hideki Hirayama*[1]; Tohru Yatabe[1]; Norimichi Noguchi[1]; Norihiko Kamata[2]; [1]RIKEN; [2]Saitama University

We demonstrated 222-273 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 NH_3 pulse-flow multi-layer growth method. We achieved low threading dislocation density (TDD), crack-free AlN buffer with atomically flat-surface. The edge and screw dislocation density of AlGaN layer on AlN template were 7.5×10^8 and 4×10^7 cm^{-2}, respectively, observed from the cross sectional TEM image. We obtained single-peaked electroluminescence (EL) from the 222-273 nm AlGaN deep-UV LEDs. The maximum output power and EQE of 222 nm and 227.5 nm LEDs were 14 μw, 0.008% and 0.15 mW, 0.2%, respectively, under RT pulsed operations. The maximum output power and EQE of 261 nm LED were 1.65 mW and 0.23%, respectively, under RT CW operation. We confirmed that the output power of AlGaN MQW LEDs were much higher than that of AlN LED.

9:00 AM
K2, Operating Temperature and Optical Dosing Effects on Deep Ultraviolet LED Lifetimes: *Craig Moe*[1]; Meredith Reed[1]; Grace Metcalfe[1]; Troy Alexander[1]; Paul Shen[1]; Michael Wraback[1]; Alex Lunev[2]; Yuriy Bilenko[2]; Xuhong Hu[2]; Ajay Sattu[2]; Jianyu Deng[2]; Maxim Shatalov[2]; Remis Gaska[2]; [1]U.S. Army Research Laboratory; [2]Sensor Electronic Technology, Inc.

Lifetime measurements on single, packaged UV LEDs were performed under constant current injection at 20mA and 75mA. The junction temperature at operation was found by micro-Raman spectroscopy to be 57°C and 184°C, respectively. Unbiased LEDs of similar characteristics placed in an oven at the equivalent operating junction temperatures showed a degradation in output power similar to that in the current injection devices during the initial 24 hours, but did not continue to degrade beyond that time. Optical dosing using 100 fs 270 nm pulses with 100 mW average power for 37 hours resulted in no loss in output power. These studies imply that device heating, and not UV radiation, is correlated with the initial drop in output power during burn-in, but is not directly linked to the entire drop in output power over the lifetime of the device.

9:15 AM
K3, Deep Ultraviolet Light Emitting Diode on Lateral Overgrown Low Defect Density $Al_xGa_{1-x}N$ Layers: *Vinod Adivarahan*[1]; Qhalid Fareed[2]; Thomas M. Katona[2]; Iftikar Ahmad[2]; Munirul Islam[2]; Seongmo Hwang[2]; Asif Khan[2]; [1]Nitek Inc.; [2]University of South Carolina

The high dislocation density in the $Al_xIn_yGa_{(1-x-y)}N$ multiple-quantum-well active regions of III-nitride deep ultraviolet (DUV) light-emitting-diodes (LEDs) significantly reduces their life-time and saturated powers. In this paper we for the first time report fabrication of $Al_xGa_{1-x}N$ template layers over c-sapphire with significantly reduced number of threading dislocations by combining lateral-epitaxial-overgrowth with a new metal-organic-hydride-vapor-epitaxy growth-process. Un-packaged deep ultraviolet LEDs (peak-emission at 280 nm) on the high-quality crack free $Al_xGa_{1-x}N$ template layers (thicknesses > 8 μm and dislocation density < $10^8/cm^2$) exhibited cw-output power-density of $16W/cm^2$ at $2kA/cm^2$ and a lifetime over 5000h. In contrast the output powers of identical geometry packaged 280 nm DUVLEDs, without the low-defect density $Al_xGa_{1-x}N$ buffers, saturated at $0.5kA/cm^2$ with a lifetime of 400h. This improvement is attributed to the low thermal-impedance and the low defect-density of the laterally overgrown $Al_xGa_{1-x}N$ layers. Details of material deposition and device fabrication and testing will be presented.

9:30 AM
K4, 280 nm-Band Quaternary InAlGaN Quantum Well Deep-UV LEDs with p-InAlGaN Layers: *Sachie Fujikawa*[1]; [1]RIKEN

Quaternary InAlGaN alloy is attracting attention as candidate material for realizing deep ultraviolet (UV) light-emitting diodes (LEDs), since efficient UV emission can be obtained on the basis of In segregation effects. Moreover, the use of p-type InAlGaN is considered to be attractive for obtaining higher hole concentration in comparison with that obtained for p-AlGaN. In this study, we demonstrated 280 nm-band InAlGaN quantum well (QW) deep-UV LEDs with p-type InAlGaN layers. The 280 nm-band InAlGaN QW deep-UV LEDs with Mg-doped InAlGaN p-type layers were fabricated on AlGaN/AlN/sapphire templates by low-pressure metal organic chemical vapor deposition (LP-MOCVD). We obtained a single-peaked operation of a quaternary InAlGaN-based UV-LED with a wavelength of 287 nm under room temperature (RT) CW operation. From this result, it is shown that quaternary InAlGaN emitting and p-type layers are attractive for achieving high-brightness (HB) deep UV-LEDs with emission at around 280 nm.

9:45 AM
K5, Deep Ultraviolet LEDs with High Internal Quantum Efficiency: Jinwei Yang[1]; *Max Shatalov*[1]; Yuri Bilenko[1]; Xuhong Hu[1]; Wenhong Sun[1]; Jianyu Deng[1]; Alex Lunev[1]; Remis Gaska[1]; Kai Liu[2]; Gintas Tamulaitis[2]; Michael Shur[2]; [1]Sensor Electronic Technology, Inc.; [2]Rensselaer Polytechnic Institute

We report on the record internal quantum efficiency (IQE) extracted from photoluminescence measurements for LEDs with peak emission wavelength at 285 nm. The IQE close to 60% was achieved by using very narrow Multiple Quantum Wells (MQWs) with the ground state energy well above the energy range, where the bands are bent by the polarization fields. This improves the electron and hole wavefunction overlap approaching the IQE that could be obtained using non-polar structures. To reach high IQEs for the electroluminescent excitation, we rely on the MQW design that provides resonant capture of electrons eliminating the need for a conventional blocking layer. Our ray tracing simulations show that the IQE of our deep UV LEDs is more than 40%. An inefficient light extraction reduces the wall plug efficiency down to 2%, which shows a tremendous potential for improving efficiency by optimizing the light extraction.

10:00 AM
K6, Lowest Noise Deep Ultraviolet LEDs: *Sergey Rumyantsev*[1]; Shayla Sawyer[1]; Yuriy Bilenko[2]; Michael Shur[1]; X. Hu[2]; A. Lunev[2]; J. Deng[2]; Remis Gaska[2]; [1]Rensselaer Polytechnic Institute; [2]Sensor Electronic Technology, Inc.

We report on comparative low frequency noise in deep UV LEDs with wavelength from 237 to 340 nm. Our results show a very low level of noise, much smaller that the noise of mercury lamps and even halogen lamps. The noise spectra of the light intensity fluctuations at frequencies f<103-104 Hz were close to the 1/f noise. The noise decreased with the increase of the LED current. At low currents, the noise level differed significantly for LEDs with different wavelengths but the difference was small at high currents. Noise properties did not degrade during the LEDs aging. These noise characteristics are important for systems applications of deep UV LEDs.

10:15 AM
K7, Late News

10:30 AM Break

Session L: UV Materials and Light Emitters II

Thursday AM May 1, 2008 | Room: Regency Ballroom B | Location: Hyatt Regency Phoenix

10:45 AM Invited

L1, Exciton Fine Structures in AlN Epilayers Grown by Metalorganic Vapor Phase Epitaxy: Takeyoshi Onuma[1]; Kei Kosaka[2]; Keiichiro Asai[2]; Shigeaki Sumiya[2]; Tomohiko Shibata[2]; Mitsuhiro Tanaka[2]; Takayuki Sota[3]; Akira Uedono[4]; *Shigefusa Chichibu*[1]; [1]Tohoku University and ERATO/JST; [2]NGK Insulators, Ltd.; [3]Waseda University; [4]University of Tsukuba

Exciton fine structures of approximately 2-µm-thick AlN epilayers grown on (0001) Al_2O_3 substrates by low-pressure metalorganic vapor phase epitaxy at NGK Insulators were studied by means of polarized optical reflectance and cathodoluminescence (CL) measurements. The epilayers commonly exhibited an atomically flat surface with monolayer steps. As a result of a reduction in the edge-type threading dislocation density (N_E) from $1x10^{10}$ to $2x10^8$ cm^{-2}, the concentration of Al vacancies was remarkably decreased, which was confirmed by the positron annihilation measurement. The relative integrated intensities of the deep emission bands between 2.5 and 4.8 eV over the near-band-edge emission were decreased by decreasing N_E lower than $1x10^9$ cm^{-2}, and spectral fine structures originating from a few free and four bound exciton lines were clearly resolved in the low-temperature CL spectra. From the energy difference between the ground- and the first-excited states, the A-exciton binding energy was determined to be approximately 51.3 meV.

11:15 AM

L2, Effect of V-Shaped Pits on the Emission Efficiency of UV-Emitting GaN/AlGaN Quantum Wells: Daniel Fuhrmann[1]; Lars Hoffmann[1]; Peter Clodius[1]; Torsten Langer[1]; Uwe Rossow[1]; Heiko Bremers[1]; Peter Hinze[2]; George Ade[2]; *Andreas Hangleiter*[1]; [1]Technical University of Braunschweig; [2]Physikalisch-Technische Bundesanstalt

While GaInN-based blue LEDs now reach external quantum efficiencies in excess of 50%, todays AlGaN-based UV-LEDs are still limited to external efficiencies of a few percent. We have recently shown that V-shaped pits in GaInN quantum wells may lead to energy barriers suppressing nonradiative recombination at dislocations and may thus be a dominant mechanism enhancing quantum efficiency. Using MOVPE growth on sapphire substrates we have grown GaN/AlGaN single quantum well structures emitting in the 340-350 nm wavelengthrange. Measurements of their internal quantum efficiency reveal record values of up to 30%. TEM images show that dislocations in these structures are decorated with V-shaped pits. Like in GaInN QWs, we observe reduced QW thicknesses on the (1-101) pit facets compared to the c plane. However, this reduction amounts to only about 25% for GaN/AlGaN QWs compared to about 70% for GaInN/GaN, resulting in less efficient screening of the dislocations.

11:30 AM

L3, A New Growth Method of High-Quality AlN on Sapphire Substrates: *Ryan Banal*[1]; Mitsuru Funato[1]; Yoichi Kawakami[1]; [1]Kyoto University

A new method for growing high-quality AlN epilayers directly on sapphire (0001) substrate has been developed. This method is based on MOVPE, where both TMA and NH3 are intermittently supplied by source pulsing, but the source pulses are overlapped to some extent. Thus, one pulse cycle (3s) consists of 1s continuous and 2s completely pulse, which lead to higher vertical and lateral growth rates simultaneously. Under optimal growth conditions, the AlN surface was atomically flat and pit-free, different from continuous or pulse supply only, both of which formed pits and/or Al particles on the surface. In addition, 600-nm-thick AlN grown by the proposed method obtained a narrow x-ray diffraction line widths of ~50 arcsec for (0002) and ~250 arcsec for (10-12), and free A-exciton emission at ~207 nm according to photoluminescence measurement at 10 K. These observations indicate that this new method is promising for obtaining high-quality AlN.

11:45 AM

L4, Reliable 310 nm LEDs on Laterally Overgrown AlN Templates: *Rakesh Jain*[1]; Xuhong Hu[1]; Alex Lunev[1]; Ajay Sattu[1]; Jianyu Deng[1]; Yuri Bilenko[1]; Max Shatalov[1]; Jinwei Yang[1]; Remis Gaska[1]; [1]Sensor Electronic Technology, Inc.

Ultraviolet light emitting diodes were deposited on 20 micron-thick AlN templates laterally overgrown over 4 micron-thick grooved AlN layers. Epitaxial layers were deposited using combination of conventional MOCVD and Migration Enhanced MOCVD (MEMOCVD®). Thick LEDs with mesa size 160 x 190 µm2 were fabricated and tested. Active area of each device was fabricated over more than 20 coalescence boundaries of laterally overgrown AlN. Devices with peak emission wavelength at 310 nm demonstrated CW output power of 1.6 mW at 50 mA current. Lifetime of the devices packaged in TO-39 cans was measured at 20 mA current without heat sink. Extracted lifetime was more than 5,000 hours. Actual testing of devices already has passed 1,200 hours, which is the highest operation time reported to date. The obtained results demonstrated high quality of laterally overgrown thick AlN and substantial improvement in the device lifetime, primarily due to reduced density of growth defects.

12:00 PM

L5, Ultraviolet Avalanche Photodiodes Based on AlGaN Grown on Free-Standing GaN and AlN Substrates: *Russell Dupuis*[1]; [1]Georgia Institute of Technology

Ultraviolet photodiodes are desired for many applications. In this work, GaN and AlxGa1-xN based ultraviolet avalanche photodiodes (APDs) grown on free-standing GaN and AlN substrates are reported. The epitaxial structures were grown by metalorganic chemical vapor deposition on free-standing GaN and AlN substrates with low dislocation density. By adopting a strain-management layer and employing optimum growth parameters, high quality, crack-free epitaxial AlxGa1-xN layers were achieved on GaN and AlN substrates. The APD devices were fabricated into 30 µm- and 50 µm-diameter circular mesas. No microplasmas or side-wall breakdown luminescence was visually observed. GaN/GaN APDs with gains > 105 have been demonstrated. AlxGa1-xN APDs on GaN substrates with mesa diameters of ~30microns achieve stable maximum avalanche optical gains of ~50 at a reverse bias voltage of ~87V with illumination at λ~250 nm. Detailed results on growth of AlGaN on AlN substrates and APD device performance of will be presented.

12:15 PM

L6, Effects of Electron and Optical Confinement on Performance of UV Laser Diodes: *Kirill Bulashevich*[1]; Mark Ramm[2]; Sergey Karpov[2]; [1]Soft-Impact, Ltd; [2]STR, Inc.

Using simulations accounting for birefringence of III-nitride materials, we investigated into the laser diodes (LDs) emitting light at 360-380 nm that was controlled by varying the InGaN composition in the multiple-quantum well active region. We have found out that both electron and optical confinement in the LD heterostructures are strongly dependent on the InGaN composition and affect remarkably the threshold current and differential quantum efficiency of the diodes. In particular, the electron leakage from the active region becomes considerable at a low InN content in the quantum wells. Spectral dispersion of the refractive indexes of In-free waveguide and cladding layers results in remarkable variations of the optical confinement factor with the emission wavelength and switching between different lateral waveguide modes. The above effects provide explanation of the observed three-fold increase in the threshold current density of the LDs with shorter wavelength. The theoretical predictions agree quantitatively well with available data.

12:30 PM

L7, Optimization of InGaN/(In,Al,Ga)N Based near UV-LEDs by MQW Strain Balancing with In-Situ Wafer Bow Sensor: A. Knauer[1]; F. Brunner[1]; S. Einfeldt[1]; V. Kueller[1]; U. Zeimer[1]; M. Weyers[1]; T. Kolbe[2]; M. Kneissl[2]; *M. Borasio*[3]; T. Zettler[3]; [1]FBH; [2]TU Berlin; [3]LayTec GmbH

Near UV LEDs with InGaN multiple-quantum-well active regions were grown by MOVPE on 2” sapphire substrates. In order to optimize the LED efficiencies MQW structures with GaN, AlGaN and InAlGaN barriers with different indium content were compared. A high resolution, in-situ wafer bow sensor allowed the measurement of the strain of the layer structure and to correlate it to the barrier layer composition during growth. The barrier composition was then correlated to the light output characteristics. By using $Al_{0.16}Ga_{0.84}N$ instead of GaN barriers the output power increased significantly. Even higher efficiencies were obtained by employing lattice matched or slightly compressively strained InAlGaN barriers. For InAlGaN barriers with indium contents ~ 4%, the shift of the near 375 to 380 nm LED emission due to the QCSE could be minimized and the external quantum efficiency has been doubled.

Session M: ZnO Light Emitters I

Thursday PM May 1, 2008 — Room: Regency Ballroom B, Location: Hyatt Regency Phoenix

2:00 PM Invited

M1, Direct Correlation between the Internal Quantum Efficiency and Photoluminescence Lifetime in Undoped ZnO Films Grown on Zn-Polar ZnO Substrates by Plasma-Assisted Molecular Beam Epitaxy: *Daiju Takamizu*[1]; Yoshio Nishimoto[1]; Shunsuke Akasaka[1]; Hiroyuki Yuji[1]; Kentaro Tamura[1]; Ken Nakahara[1]; Tetsuhiro Tanabe[1]; Hidemi Takasu[1]; Masashi Kawasaki[2]; Takeyoshi Onuma[3]; Shigefusa Chichibu[3]; [1]Rohm Company, Ltd.; [2]WPI Advanced Institute for Materials Research and Institute for Materials Research, Tohoku University; [3]Institute of Multidisciplinary Research for Advanced Materials, Tohoku University

The equivalent internal quantum efficiency at 300 K of the near-band-edge excitonic photoluminescence peak in ZnO epilayers grown by plasma-assisted molecular beam epitaxy on Zn-polar ZnO substrates was directly correlated with the photoluminescenc lifetime for the first time. This relation seems to be universal for O-polar ZnO films grown by other methods. A considerable reduction in the concentrations of structural and point defects was demonstrated by using a ZnO homoepitaxial substrate and high T_g growth conditions. As a result of the overall process optimization, a long photoluminescenc lifetime of 3.0 ns at 300 K was obtained for the epilayer grown at 800°C, which exhibited a record high equivalent internal quantum efficiency value of 15% under an excitation density of 1 W/cm^2. The homoepitaxial Zn-polar ZnO films grown by molecular beam epitaxy are coming to be used for p-n junction devices.

2:30 PM

M2, ZnO Lighting Emitting Diodes Using Sb-Doped p-Type ZnO Thin Films: *Jianlin Liu*[1]; Sheng Chu[1]; Leela Mandalapu[1]; Jae-Hong Lim[1]; Zheng Yang[1]; [1]University of California

We report our effort on p-type Sb-doped ZnO epitaxial films on Si and sapphire substrates based on plasma-assisted molecular beam epitaxy (MBE). The hole concentrations with a wide range were achieved by tuning the growth parameters. X-ray photoelectron spectroscopy and photoluminescence measurements confirmed the theoretical prediction that the Sb doping mechanism is the formation of complex shallow acceptor SbZn+2VZn, with a low ionization energy of about 150meV. ZnO p-n homojunction light emitting diodes (LED) were fabricated based on the p-type Sb-doped ZnO/n-type Ga-doped ZnO. Low specific resistivity Au/NiO and Au/Ti contacts were deposited on top of the p-type and n-type layers, respectively, and the contacts characteristics have been systematically studied. Current-voltage measurements of the devices showed typical rectifying behavior. Strong near-band edge emissions were observed at room and low temperatures in electroluminescence measurement. This result suggests that Sb-doped p-type ZnO is very promising in future optoelectronic devices.

2:45 PM

M3, ZnO Nanowire Based Heterostructure Diodes: *Sai Giridhar S*[1]; Pritesh Hiralal[2]; Husnu Unalan[2]; Sivaramakrishnan S[1]; Venkataramanaiah K[1]; Gehan Amaratunga[2]; [1]Sri Sathya Sai University; [2]University of Cambridge

We report a simple method to fabricate ZnO nanowire based Heterostructure Schottky Diodes in a configuration that has shown U.V electroluminescence. The device consists of vertically oriented ZnO nanowires grown by a simple hydrothermal method on ITO substrates. Scanning Electron microscopy and X-ray diffraction show the nanowires to be vertically oriented and single crystalline wurtzite ZnO. The P.L spectrum shows an instense U.V peak at 382nm and a low peak around 530nm. The nanowires are well insulated by a high molecular weight polymer thin film. For an LED configuration hole injection is provided by a higly doped p-type polymer and electron injection occurs through the transparent ITO layer. A Schottky contact is achieved by evaporating Au on the polymer. The I-V curves show excellent rectification characteristics. Overall this is a very simple and scalable method to fabricate Heterostructure Diodes based on ZnO nanowires that could lead to U.V electroluminescent devices.

3:00 PM

M4, Temperature-Dependent Behavior of n-ZnO Nanorods/p-Si Diodes and Their Transport Mechanism: *Yoon-Bong Hahn*[1]; N. Koteeswara Reddy[1]; Qurashi Ahsanulhaq[1]; Jin Hwan Kim[1]; [1]Chonbuk National University

This work explores the transport mechanism of n-ZnO nanorods/p-Si heterojunction devices and their temperature-dependent behavior. The ZnO nanorods grown on ZnO-coated silicon substrate are highly crystalline, grown along the [0001] direction. Different metal contacts (M = Ag, Al, In, Sn) were examined by current versus voltage measurements. The M/ZnO nanorods except Al/ZnO exhibited a good ohmic behaviour. The p-n junction diode with the configuration of In/n-ZnO nanorods/ZnO/p-Si showed an excellent stability over the temperature range of 20-150°C due to highly doped p-type Si substrate. The as-grown diodes showed, at all temperatures, a good p-n junction behavior and exhibited a diode quality factor of ~1.39 at lower voltages. The device also showed a low saturation current and allowed high current in the order of 10-2 A. The current transport mechanism in the device was limited by three types of mechanisms depending on applied bias voltage and temperature.

3:15 PM

M5, Optical and Structural Properties of Homoepitaxial Grown ZnO Epilayers by Chemical Vapour Deposition: Markus Wagner[1]; Ronny Kirste[1]; Til Bartel[1]; Jan-Hindrik Schulze[1]; Ute Haboeck[1]; *Axel Hoffmann*[1]; Joachim Sann[2]; Stefan Lautenschläger[2]; Christian Neumann[2]; Bruno Meyer[2]; [1]Technische Universität Berlin; [2]Justus Liebig University

The availability of ZnO substrates enables the homoepitaxial growth of ZnO layers without concern for different thermal expansion coefficients and lattice constants. Consequently, completely relaxed strain-free epilayers should be achievable, although residual strain may result from diffusion of impurities into the epilayer. We present photoluminescence, cross-sectional micro-Raman, high resolution transmission electron microscopy (HRTEM), and x-ray diffraction measurements of homoepitaxial grown epilayers on ZnO substrate with different surface polarity (O-face and Zn-face termination). The epilayers show superior structural quality indicated by a reduction of the rocking curve FWHM on the (0002) reflection compared to the substrate. The low temperature photoluminescence of the O-face and Zn-face terminated samples reveal major differences in dependence on the surface polarity of the substrate. Several new excitonic transitions can be observed in O-face samples. The formation of strain due to impurity diffusion from the substrate is discussed as function of the surface polarity.

3:30 PM Break

Session N: ZnO Light Emitters II

Thursday PM Room: Regency Ballroom B
May 1, 2008 Location: Hyatt Regency Phoenix

3:45 PM

N1, Structural and Optical Properties of Ion-Implanted ZnO Nanorods: *Sang-Wook Han*[1]; [1]Chonbuk National University

We investigated the structural and optical properties of ion-implanted ZnO nanorod arrays with various techniques. Vertically-aligned ZnO nanorods were fabricated with a MOCVD procedure. For the p-doping of the ZnO nanorods H+ and N+ ions with 50, 70, 90, and 120 keV was implanted with ion flux of 1016 and 1017 particles/cm2 at room temperature. XRD measurements demonstrated that all ion-implanted ZnO nanorods still maintained a wurtzite structure. TEM measurements revealed that dark spots spread over the entire length of the nanorods, suggesting that the ions were uniformly implanted over the nanorods. The dark spots were ascribed to ion damages. Extended X-ray absorption fine structure (EXAFS) measurements at Zn K-edge confirmed the XRD and TEM results that the ion implantation slightly caused the structural damage. PL measurements demonstrated a blue shift and decrease of the main transition peak due to the ion implantation.

4:00 PM

N2, High-T Photoluminescence and Photoluminescence Excitation Characteristics of ZnO Nanowire Arrays Grown on c-Si for Opto-Electronic Device Applications: *Arti Gupta*[1]; Mones Omari[1]; Nikolai Kouklin[1]; [1]University of Wisconsin, Milwaukee

Compared with GaN, ZnO demonstrates much larger free-exciton binding energy, ~60meV, which ensures stable high-efficiency excitonic emission at temperatures up to ~600-700 K. With the device sizes fast approaching nanoscale and for the possibility to achieve lasing, the research focus on ZnO has shifted towards nanowires, which can now be synthesized economically as highly faceted single crystals on a variety of substrates, including optically-inefficient Si. In this presentation, we are to address the properties and processes controlling growth and high-T light emission characteristics of highly crystalline ZnO nanowires synthesized on c-Si by a catalyst-assisted vapor-liquid-solid route. A contribution of various mechanisms underlying near-band-edge photoluminescence (PL) will be discussed based on the results of performed temperature-, power-, time-and excitation-dependent spectral characterizations and measurements. The properties and processes underlying sub-band gap (defect) emission at alleviated T range will be also presented and discussed.

4:15 PM

N3, Transparent Al-Doped ZnO Thin Films Synthesized by RF Magnetron Sputtering: *Soo Young Seo*[1]; Chang-Ha Kwak[1]; Seon-Hyo Kim[1]; Sun-Hong Park[2]; Sang-Wook Han[3]; [1]POSTECH; [2]Research Institute of Industrial Science and Technology; [3]Chonbuk National University

Transparent and conductive Al-doped zinc oxide thin films were fabricated on Al2O3 substrates by a RF-magnetron sputtering procedure from ZnO targets with various Al concentrations. The aluminum concentration was varied from 2 to 5 weight %. The structural and optical properties of the Al-doped ZnO thin-films were characterized using field emission scanning electron microscopy (FE-SEM), X-ray diffraction (XRD), extended X-ray absorption fine structure (EXAFS), UV-VIS-IR and photoluminescence (PL) measurements. The XRD and EXAFS measurements revealed that the Al-doped ZnO thin-films had a wurtzite crystal structure and had the (002) preferred orientation. We did not observed any extra phase. The UV-VIS-IR measurements showed that the visual light transparency of the films was 90%. The band gap of the films was about 3.35 eV and the visual light absorption edge was about 350 nm. We will discuss the chemical and optical properties, comparing with the structural properties and the Al-doping ratios.

4:30 PM

N4, Growth Behavior and Microstructure of ZnO Epilayer on (100) Gamma-LiAlO$_2$ Substrate by Chemical Vapor Deposition: *Liuwen Chang*[1]; Mitch Chou[1]; Teng-Hsing Hwang[1]; Jih-Jen Wu[2]; Chun-Wei Chen[3]; Uwe Jahn[4]; [1]Sun Yat-Sen University; [2]Cheng Kung University; [3]Taiwan University; [4]Paul-Drude Institute for Solid State Electronics

Low lattice-mismatched (100) gamma-LiAlO$_2$ substrate were employed to grow ZnO epitaxial films by chemical vapor deposition. The influence of growth temperature on growth mode of ZnO was investigated. At a low deposition temperature of 575°C, three orientations of nuclei: (10-11), (10-10) and (0001) were observed in the early stage of growth, whereas the (0001) ZnO possessed the highest growth rate and grew laterally over the (10-10) and (10-11) ZnO nuclei in the late stage of growth. The nucleation of (10-11) ZnO was completely suppressed at 640°C, and only (10-10) ZnO nuclei were observed on further increasing deposition temperature to 675°C. The (0001) ZnO film possessed a high efficiency of near band-edge emission and the FWHM of the emission peak is about 11meV. Details will be given based on microstructure characterization.

4:45 PM

N5, ZnO Doping by Combustion Synthesis: *JING LI*[1]; Rafael Garcia[2]; Fernando Ponce[2]; [1]Xiamen University and Arizona State University; [2]Arizona State University

As a wide direct band gap semiconductor material, ZnO has attracted much attention due to its extensive application in electronic and optoelectronic devices. Electronic doping of ZnO has been an important issue. The common n-type dopants are III group elements such as indium, alminiumn and gallium, while silver, lithium or nitrogen is ever reported to be used in p-type doping. In our report, a one-step synthesis method by solution combustion technology was applied to produce ZnO powder, using the nitrates of the metals as oxidizer agents and carbohidrazine as fuel. The subsequent annealing treatment was performed to improve the materials quality. The doping concentration's effect on the structure and luminescence of ZnO was investigated by x-ray diffraction pattern (XRD) and cathodoluminescence (CL) spectroscopy.

5:00 PM

N6, Improvement of Light Extraction from GaN-Based Light-Emitting Diodes with Nano-Patterned Surface Using Porous Anodic Aluminum Oxide Templates: *Tao Dai*[1]; Bei Zhang[1]; XiangNing Kang[1]; Kui Bao[1]; WenZhu Zhao[1]; DongSheng Xu[1]; GuoYi Zhang[1]; Zizhao Gan[1]; [1]Peking University

We demonstrate a manufacturing approach of nanostructures on the surfaces of GaN-based LED to improve the light extraction efficiency by using anodic aluminum oxide (AAO) as the nano-pattern transfer template. The surface of GaN-based LEDs was nano-patterned by dry etching using the AAO template as etching mask. The pore diameter and interpore distance of AAO template were in the range of 190±40 nm and 320±40 nm, respectively. We are also very interested to find out a correlation between the enhancement extraction factor and the density of patterned nanopores on the surface of LEDs. The enhancement of light output power varied from 20% to 70% as the pore density increased from 1×10^8 to 8×10^8/cm^2 at 20 mA. This work is supported by 863 program (2006AA03A113),973 program (2007CB307004) and NSF (60276034, 60577030 and 60607003) of China.

5:15 PM

N7, Optoelectronic Properties of Bragg Layers for GaN Based LEDs and VCSELs: Maria Linnick[1]; Sheila Luke[1]; Abhishek Motayed[2]; *Aris Christou*[1]; [1]University of Maryland; [2]Howard University

Short-wavelength VCSELS are typically important for high-density optical memory and optical imaging systems. An AlGaN/GaN LED and VCSEL was designed for operation at wavelength of 360 nm. The design process consisted of the calculation of the optoelectronic properties of the DBR layers over a wide range of compositions and optimization of the parameters for DBR stacks, active region. The InGaN/AlGaN material system was optimized for constructing DBR stacks in order to minimize power dissipation and to achieve high reflectivity. A reflectivity of 99% was calculated for 33 pairs in the bottom DBR stack and 97% was calculated for 30 pairs in the top DBR stack. An external quantum efficiency of 85% has been achieved through parametric optimization. In this particular structure, a MQW GaN/ Ga0.8Al0.2N (x10) was used.

Session O: Nano-Wire Based Light Emitters

Friday AM
May 2, 2008

Room: Regency Ballroom B
Location: Hyatt Regency Phoenix

8:30 AM Invited

O1, Ti-Mask Selective Area Growth of GaN Nanowalls by RF-Plasma Assisted Molecular Beam Epitaxy: *Akihiko Kikuchi*[1]; Katsumi Kishino[1]; Takayuki Hoshino[1]; [1]Sophia University

Two dimensional GaN nano-crystals named "nanowall" were successfully fabricated on GaN template by RF-plasma assisted MBE using Ti-mask selective area growth technique. Typical size of the GaN nanowalls was 150~300nm in width, ~1000nm in height and over 160µm in length. The side planes of the GaN nanowalls were very smooth and perpendicular to the (0001) substrate surface. The top facets of the nanowalls were varied from polar (0001) to semi-polar plane by changing the growth conditions. From TEM observation, it was observed that threading dislocations propagated in the GaN template were stopped at the nanowall/template interface. The GaN nanowalls with InGaN quantum wells showed intense PL emission at room temperature and wave guide effect for PL emission light. The GaN nanowall can be designed in various shapes e.g. ring-cavity and branching, and is an attractive material for nano-photonic/-electronic devices such as nano-LDs, nano-LEDs, optical-circuits, FETs, and so on.

9:00 AM

O2, Cathodoluminescence Microscopy of GaN Nanopyramids Grown on Si(111): *Frank Bertram*[1]; Sebasitian Metzner[1]; Juergen Christen[1]; H. Tang[2]; L. Lapointe[2]; [1]University of Magdeburg; [2]NRCC

A 10nm thick MBE grown AlN buffer on Si(111) was patterned into an array of hexagonal pads with openings from 0.5 to 1.5µm. The subsequent GaN overgrowth was carried out forming distinct GaN nanopyramids terminated by {10-12} sidefacets. The GaN pyramids were covered with an InGaN quantumwell to form an InGaN quantumdot at the very top. The spatially integrated cathodoluminescence (CL) spectrum of a single pyramid at 5K exhibits multiple sharp emissionlines over a wide spectral range from 357 to 500nm. No CL emission was observed outside the pyramid. The intensity drops significantly at the pyramidedges. The topregion of the pyramid exhibits a bright hexagonally shaped contrast dominated by GaN emission. On the contrary, the InGaN luminescence is very intense at the pyramidbase. The InGaN intensity decreases and the emission blueshifts from 405 to 375nm from the base to the top of the pyramid, respectively.

9:15 AM

O3, Well-Arranged InGaN/GaN Nanocolumns on GaN Template with Ti-Nanoholes Grown by RF-Assisted Molecular Beam Epitaxy: *Hiroto Sekiguchi*[1]; Jo Tanaka[1]; Akihiko Kikuchi[1]; Katsumi Kishino[1]; [1]Sophia University

GaN nanocolumns are self-organized columnar nano-crystals. They have high optical properties due to dislocation-free nature. Thus, the nanocolumn-based light emitting devices are expected to have high-performance and high-efficiency. In this study, we report that well-arranged InGaN/GaN nanocolumns, which consisted of a single InGaN well of ??-nm-thickness sandwiched in between GaN nanocolumns at the top and bottom, were grown on GaN template by selective area growth (SAG) of nanocolumn using Ti-nano-hole-patterns. The nanocolumns were selectively grown at each nano-hole. Accordingly the well-arranged, periodic nanocolumns of 400-nm-period, 300-nm-diameter, and 2-µm-height were fabricated. Photoluminescence spectra of the well-arranged InGaN/GaN nanocolumns were evaluated at room temperature. The well-arranged nanocolumn sample emitting at 650nm showed a stronger PL peak intensity and a narrower PL spectrum compared with those of self-organized 8-period InGaN/GaN nanocolumns. This result indicates that the SAG of nanocolumn growth contributes to a higher crystal-quality and emission uniformity of InGaN/GaN nanocolumns.

9:30 AM

O4, Low-Temperature Cathodoluminescence Spectroscopy of Individual GaN Nanowires and Related Nanoparticles Grown by Catalyst-Free Molecular Beam Epitaxy: *Lawrence Robins*[1]; Kris Bertness[1]; Joy Barker[1]; Norman Sanford[1]; John Schlager[1]; [1]National Institute of Standards and Technology

Low-temperature, spectroscopic CL measurements were performed on individual GaN nanowires and related nanoparticles. In addition, the dependence of the CL of individual nanowires on temperature, from 12 K to 100 K, and polarization was examined. The CL spectra of GaN nanowire/nanoparticle clusters contain free and donor bound exciton peaks, as well as "unusual" peaks denoted the Y lines, which are ascribed to structural defects. According to the new results, straight nanowires do not produce the Y lines, while particles with fin-shaped, y-shaped or pyramidal morphologies produce Y lines and other defect-related peaks. The excitonic peak in nanowires underwent a slight redshift with increasing temperature, which was less than the redshift of the GaN bandgap. Polarization analyzed measurements showed that for polarization perpendicular to 0001, the donor-bound A exciton is the dominant peak. However, for polarization parallel to 0001, the higher-energy donor-bound B exciton is dominant.

9:45 AM

O5, High-Quality GaN Thin Film with the Coalescence Overgrowth of Nanocolumns: Tsung-Yi Tang[1]; Wen-Yu Shiao[1]; Yung-Sheng Chen[1]; Kent Averett[2]; John Albrecht[2]; *C. C. Yang*[1]; [1]National Taiwan University; [2]Air Force Research Laboratory

We demonstrate the coalescence overgrowth (with MOCVD) of GaN nanocolumns (grown with MBE) for fabricating high-quality GaN thin film. Due to the lateral strain relaxation, low-dislocation density, oriented GaN nanocolumns have been successfully grown. However, for practical implementation of device, coalescence overgrowth is needed. Based on the measurements of depth-dependent X-ray diffraction, transmission electron microscopy, photoluminescence, and cathodoluminescence, we show that the crystal quality and optical property of an overgrown GaN thin film are superior to those of a standard high-quality GaN thin film directly grown on sapphire substrate. In particular, it was discovered that based on nanocolumns of 100 nm in diameter and 10^9 cm^{-2} in column density, the overgrowth beyond 400 nm in thickness led to better and better crystal quality as the growth layer becomes thicker and thicker. The crystal quality becomes better than the standard GaN thin film when the overgrowth thickness reaches 2 microns.

10:00 AM

O6, Nanowire Templated Lateral Epitaxial Growth (NTLEG) of Low Dislocation Density GaN: *George Wang*[1]; Qiming Li[1]; J. Randall Creighton[1]; [1]Sandia National Laboratories

We present here an innovative technique employing vertically aligned GaN nanowire arrays as 3D strain-compliant templates for the lateral growth and coalescence of high quality GaN films on sapphire. In contrast to current epitaxial lateral overgrowth techniques, this approach, referred to here as "nanowire templated lateral epitaxial growth" (NTLEG), requires no growth interruption or costly patterning. Using metal-catalyzed MOCVD, we have achieved the growth of highly aligned and dense arrays of single crystalline GaN nanowires uniformly on unpatterned 2-inch diameter sapphire. From these nanowire arrays, we have been able to demonstrate fully coalesced, non-polar a-plane GaN NTLEG films. The growth and characterization of the nanowire arrays and NTLEG films will be discussed. 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. This work is supported by DOE EERE/NETL.

10:15 AM

O7, Late News

10:30 AM Break

Session P:
Novel Applications

Friday AM — Room: Regency Ballroom B
May 2, 2008 — Location: Hyatt Regency Phoenix

10:45 AM Invited

P1, Quantum Dot Based Light Emitting Devices for Single Photon Emission Based on Nitrides and Selenides: *Detlef Hommel*[1]; Stephan Figge[1]; Carsten Kruse[1]; Arne Gust[1]; Christian Tessarek[1]; Kathrin Sebald[1]; Joachim Kalden[1]; Thomas Meeser[1]; Juergen Gutowski[1]; Robert Arians[2]; Tilmar Kuemmell[2]; Gerd Bacher[2]; [1]University of Bremen; [2]University of Duisburg-Essen

Semiconductor quantum dot (QD) based single photon emitters are crucial for quantum computing and cryptography. However, most of the promising concepts are limited to low temperatures. This might be circumnavigated by using wide band-gap materials as they exhibit a strong carrier confinement and therefore enhanced temperature stability. In this study we report on QD devices based on nitride as well as ZnSe materials. For optically excited GaN structures emission lines from QDs can be observed up to 150 K. In the case of ZnSe even the first electrically driven quantum dot device exhibiting a single emission line at room temperature will be presented. We will give a thorough overview on the possibilities and limitations of the two material systems.

11:15 AM

P2, Nitride /Organic Hybrid Heterostructures for Novel Optoelectronic Devices: *Hyunjin Kim*[1]; Qiang Zhang[1]; Arto Nurmikko[1]; Qian Sun[2]; Jung Han[2]; [1]Brown University; [2]Yale University

We report the investigation of the GaN/organic semiconductor hybrid heterojunction device as a part of ongoing efforts to explore novel semiconductor materials and to improve the performance of GaN-based optoelectronic devices. The GaN/CuPc hybrid device shows quite robust and strong rectifying characteristics. Also it shows efficient photocurrent response at the absorption wavelength of both GaN and CuPc, which enjoy evident ease in electron and hole transport across the interface. This device shows 1% estimated external quantum efficiency at 390nm wavelength, in case around 2 to 3% of incident light is absorbed in thin InGaN SQW layer. This result suggests the utility of organic/inorganic hybrid heterojunction device in novel solar cell or sensitive photodetector with versatility.

11:30 AM

P3, Near-UV Emitting GaN/GaInN/AlGaN QW LEDs: Efficiency Enhancement and Use in Integrated In_2O_3-Based Ozone Sensors: *Markus Maier*[1]; Chunyu Wang[1]; Claus-Christian Röhlig[1]; Michael Kunzer[1]; Thorsten Passow[1]; Volker Cimalla[1]; Klaus Köhler[1]; Joachim Wagner[1]; Oliver Ambacher[1]; [1]Frauhofer Institute for Applied Solid-State Physics

The monolithic integration of near-UV LEDs and metal-oxide sensing layers opens the possibility for the realization of compact and robust gas sensors with low power consumption. The efficiency of such near-UV emitting GaInN LEDs is shown to depend significantly on the defect density (DD) of the underlying GaN. LED structures covering the wavelength range 370-420 nm were grown by MOVPE (a) directly on sapphire, (b) on low dislocation density GaN-templates on sapphire, and (c) on free-standing HVPE grown GaN-substrates, with DD from 10^9 cm^{-2} (a) to $4x10^7$ cm^{-2} (c). Upon reduction of the DD a clear increase in electroluminescence (EL) efficiency is observed. For the integrated LED/In_2O_3 ozone sensor, a nano-crystalline In_2O_3 layer was deposited on the backside of a 400-nm-emitting LED, using the UV light for resetting the sensing layer. Thus a differential measurement mode could be realized with an unprecedented sensitivity for this sensor-type of <40 ppb O_3.

11:45 AM

P4, Microarrays of Blue-Green LEDs and Imaging Fibers for Vertebrate Visual System Development Studies: *Heng Xu*[1]; Kristina Davitt[2]; Wei Dong[1]; Yoon-Kyu Song[1]; Carlos Aizenman[1]; Arto Nurmikko[1]; [1]Brown University; [2]Ecole Normale Superieure

We have developed a micro-scale endoscopic optical image projection device, integrating an InGaN MQW blue/green two-dimensional (2D) LED array to a multicore imaging fiber. A scalable matrix addressing scheme was used for the electrical access to individual elements in the device. A prototype 10x10 element array was fabricated by specialized device process flow, using deep reactive ion etching and polyimide etch-back processes for device isolation and planarization. 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 an application in studies of vertebrate visual system development, selected illumination patterns have been projected to the eye of *Xenopus laevis* tadpoles with either the electrical or optical recording of the animal's optic tectum (visual center of the tadpole), so as to measure and compare the size of the receptive and projective field at different developmental stages.

12:00 PM

P5, Optical Properties of InGaPN/GaPN Multi Quantum Well Light-Emitting Diode with High In Content on Si Substrate: *Soo Young Moon*[1]; [1]Toyohashi University of Technology/Department of Electrical and Electronic Engineering

There has recently been a great deal of interest in the high-quality growth of III-V compound semiconductors on Si for OEIC. Nitrogen incorporation into III-V semiconductors, such as GaPN, InGaPN, and GaAsPN alloys, results in numerous effects, such as a dramatic reduction in the fundamental bandgap energy and a significant decrease in the lattice constant. In this study, an InGaPN/GaPN MQW structure was grown on a Si substrate by using MBE apparatus. Thus, we have fabricated the micro-size InGaPN/GaPN MQW LED for fabricating LED with high optical efficiency. All EL emission peak wavelengths are observed at approximately 642 nm. The FWHM of EL spectrum is 65 nm at 10 mA. Therefore, the FWHM of InGaPN/GaPN MQW LED was smaller that that of InGaPN/GaPN DH LED. In particular, MQW structure LED is still very promising for the fabrication of high-performance LEDs on Si substrate as optical device of OEIC.

12:15 PM

P6, High Reliable BeZnSeTe/MgZnCdSe II-VI Compound Green Light Emitting Devices on InP Substrates: *Ichirou Nomura*[1]; Tomoya Ebisawa[1]; Shun Kushida[1]; Kazuki Toyama[1]; Soh Kuroiwa[1]; Katsumi Kishino[1]; [1]Sophia University

Green light emitting devices based on BeZnSeTe/MgZnCdSe II-VI compounds on InP substrates were fabricated. The devices consisted of a BeZnSeTe QW active, MgSe/BeZnSeTe superlattice barrier, MgSe/ZnCdSe superlattice n-cladding, and MgSe/BeZnTe superlattice p-cladding layers. Pure green emissions around 537 nm were obtained. Aging tests of the devices showed a long lifetime operation as long as 4800 h without any rapid or catastrophic degradation. This is a great advancement in the device lifetime compared with precedent blue-green ZnCdSe/MgZnSSe II-VI devices, in which the lifetimes were several hundred hours. This experiment indicates that the BeZnSeTe/MgZnCdSe devices are highly reliable. To date we have developed MgZnCdSe, BeZnTe, and BeZnSeTe II-VI compounds on InP substrates for green light emitting devices. Especially, BeZnSeTe is promising as an active layer material of highly reliable green devices. The inclusion of BeSe and BeTe in BeZnSeTe is effective for enhancing the lattice-hardness, which contributes to lengthening the device lifetime.

12:30 PM

P7, Spectroscopy of AlN Epilayers Implanted with Ytterbium Ions: *Wojciech Jadwisienczak*[1]; Henryk Lozykowski[1]; Abdelhak Bensaoula[2]; Chris Boney[2]; Andre Anders[3]; [1]Ohio University; [2]University of Houston; [3]Lawrence Berkeley National Laboratory

In this presentation we report on luminescence of AlN grown by molecular beam epitaxy on Si substrates and implanted with Yb^{3+} ions. Ytterbium is one of a few lanthanide ions which has not been investigated as an optically active center in crystalline AlN host. The luminescence of AlN:Yb^{3+} was measured in 8-400 K and revealed week thermal quenching. In general, observed PL and CL spectra of Yb-doped AlN are complex. The number of observed 4f-shell emission lines indicates that Yb ions occupying substitutional site with C_{3v} symmetry are involved in different optically active centers. The nature of these centers and the excitation mechanism was investigated using photoluminescence excitation spectroscopy and site selective spectroscopy in the spectral range from 200-800 nm. Based on obtained experimental data we will discus the excitation mechanism for Yb^{3+} ions in AlN which can be generalized for all rare earth RE^{3+} ions in III-nitride semiconductors.

12:45 PM Closing Remarks

NOTES

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ISSLED History

The International Symposium on Semiconductor Light Emitting Devices is a continuation of the biennial meeting previously named International Symposium on Blue Lasers and Light Emitting Devices. The first meeting was chaired by Professor Akihiko Yoshikawa at Chiba University in Japan in 1996. The sixth meeting in the series was chaired by Professor Bernard Gil in Montpelier, France, in 2006. This seventh meeting is the first one to be held in the United States.

About TMS

The Minerals, Metals & Materials Society (TMS) is the professional organization encompassing the entire range of materials science and engineering, from minerals processing and primary metals production to basic research and the advanced applications of materials.

Included among its professional and student members are metallurgical and materials engineers, scientists, researchers, educators and administrators from more than 70 countries on six continents.

TMS' mission is to promote the global science and engineering professions concerned with minerals, metals and materials. To learn more or to become a member, visit **www.tms.org** or www.materialstechnology.org.

ISSLED 2008
International Symposium on Semiconductor Light Emitting Devices

At-A-Glance

	Regency Ballroom Foyer	Regency Ballroom A	Regency Ballroom B	Regency Ballroom C
Sunday PM	Registration (3:00-7:30 PM)	Welcome Reception and Exhibit (6:00-7:30 PM)		
Monday AM	Registration (7:30 AM-5:00 PM)	Exhibit (8:00 AM-5:00 PM)	Plenary Session (8:30-9:30 AM) Session A: Photonic Crystal LEDs (9:30-10:45 AM) Session B: Visible LEDs I (10:45 AM-12:45 PM)	
Monday PM			Session C: Visible LEDs II (2:00-3:45 PM) Session D: Visible LEDs III (3:45-5:30 PM)	
Tuesday AM	Registration (7:30 AM-5:00 PM)	Exhibit (8:00 AM-5:00 PM)	Session E: Non-Polar LEDs I (8:30-10:45 AM) Session F: Non-Polar LEDs II (10:45 AM-12:45 PM)	
Tuesday PM			Session G: Non-Polar LEDs III (2:00-3:45 PM) Session H: Visible LEDs IV (3:45-5:30 PM)	
Wednesday AM	Registration (7:30 AM-12:00 Noon)	Exhibit (8:00 AM-12:00 Noon)	Session I: Visible LEDs V (8:30-10:45 AM) Session J: Materials Growth and Characterization (10:45 AM-12:45 PM)	
Thursday AM	Registration (7:30 AM-5:00 PM)	Exhibit (8:00 AM-5:00 PM)	Session K: UV Materials and Light Emitters I (8:30-10:45 AM) Session L: UV Materials and Light Emitters II (10:45 AM-12:45 PM)	
Thursday PM			Session M: ZnOLight Emitters I (2:00-3:45 PM) Session N: ZnOLight Emitters II (3:45-5:30 PM)	Banquet (6:00-8:00 PM)
Friday AM	Registration (7:30-10:30 AM)		Session O: Nano-Wire Based Light Emitters (8:30-10:45 AM) Session P: Novel Applications (10:45 AM-1:00 PM)	