## Electronic Materials and Processing
## Room: 101 B - Session EM+NS+SS+TF-FrM

### Growth and Characterization of Group III-Nitride Materials
**Moderator:** N. Dietz, Georgia State University, I.T. Ferguson, University of North Carolina at Charlotte

9:00am **EM+NS+SS+TF-FrM3 Photoluminescence and Kelvin Probe Studies of Mg-doped GaN**, ***J.D. McNamara***, *A.A. Baski, M.A. Reshchikov*, Virginia Commonwealth University

High-quality p-type gallium nitride (GaN) can only be achieved by doping with magnesium (Mg). However, some unidentified point defects are also present in this material and detrimentally affect the properties of GaN thin films and related devices. Analyzing the photoluminescence (PL) spectra of GaN thin films provides valuable information regarding point defects in GaN. Additionally, the Kelvin probe method supplies complementary information about the electrical and optical properties of GaN near the surface. We have demonstrated in the past that simple phenomenological models based on rate equations are able to describe the results obtained in PL and Kelvin probe experiments. In particular, the concentrations of defects, their carrier-capture parameters, and energy levels can be found from PL measurements. The Kelvin probe method allows us to accurately determine the conductivity type for GaN thin films where Hall effect measurements are ambiguous. Temperature-dependent surface photovoltage (SPV) studies provide useful data about the surface band bending in dark, during illumination and the subsequent restoration after illumination. Using these methods, we have studied Mg-doped p-type GaN samples grown by various techniques. Interestingly, the PL spectra at low temperatures for several different samples contain different dominant bands – the ultraviolet luminescence (UVL), blue luminescence (BL) and green luminescence (GL) bands – which are all related to different defects. In some samples, the UVL band is quenched abruptly at a characteristic temperature (between 100-200 K) which can be tuned by excitation intensity. In other samples, the UVL band demonstrates no tunable quenching and a much faster decay (orders of magnitude) after pulsed excitation in time-resolved PL experiments. Our temperature-dependent Kelvin probe measurements show a conversion of the conductivity type at low temperatures under UV illumination. The temperature of the change in conductivity type varies between the samples and is also tunable with excitation intensity. This is consistent with PL results and can be explained by a switch in the majority charge carrier. These results are indicative of some special features of the nonradiative defects in p-type GaN (deep donors which have large capture cross-sections for both carriers). Although all the samples are Mg-doped and have comparable p-type conductivity, we assume that unidentified point defects in Mg-doped GaN are responsible for the diverse behaviors which have been observed. By modeling and comparing data from PL and Kelvin probe studies, we can acquire a better understanding of the properties of p-type GaN materials.

9:20am **EM+NS+SS+TF-FrM4 Surface Structure, Polarity and Surface Kinetics of InN Grown by Plasma – Assisted Atomic Layer Epitaxy: A HREELS Study**, ***A. Acharya***, Georgia State University, *N. Nepal, C. Eddy,* Naval Research Laboratory, *B. Thoms*, Georgia State University

The surface bonding configuration and kinetics of hydrogen desorption from InN grown on Si (100) by plasma-assisted atomic layer epitaxy have been investigated. High resolution electron energy loss spectra exhibited loss peaks assigned to a Fuchs-Kliewer surface phonon, N-N and N-H surface species. The observation of N-H but no In-H surface species suggests N-polar InN. Isothermal desorption data was best fit by the first-order desorption kinetics with an activation energy of 0.88 ± 0.06 eV and pre-exponential factor of $(1.5 \pm 0.5) \times 10^5$ $s^{-1}$. The lower activation energy, the first-order desorption kinetics and surface N-N vibrations are attributed to surface defects.

9:40am **EM+NS+SS+TF-FrM5 A Vertical Superatmospheric Pressure MOCVD Reactor for InGaN Growth**, ***A.G. Melton***, *P. Davis, M. Uddin, E.B. Stokes*, University of North Carolina at Charlotte

Thermodynamic calculations have predicted that elevated nitrogen pressure over the $In_xGa_{1-x}N$ growth surface will suppress indium evaporation, thus enabling growth at higher temperature. This is expected to result in both better adatom mobility on the growth surface and improved pyrolization efficiency of ammonia (thus reducing nitrogen vacancies). These two effects are expected to result in improved internal quantum efficiency of high indium $In_xGa_{1-x}N$ materials. A vertical, rotating susceptor MOCVD reactor capable of superatmospheric growth pressures (up to 3 bar, absolute) has been designed and built at UNC Charlotte. The intended application of this reactor is to explore the use of elevated growth pressure in suppressing nitrogen vacancies, indium desorption, and phase separation in high-indium $In_xGa_{1-x}N$ alloys, such as those within the “green gap”. The reactor is capable of growth on a single 2” diameter wafer at a time and has been designed to minimize turbulence using computational fluid dynamics simulations. The reactor design and results from early growth runs will be presented here. X-ray diffraction and confocal photoluminescence are used to evaluate macroscopic and spatially resolved phase separation, respectively, as well as composition and crystal quality.

10:00am **EM+NS+SS+TF-FrM6 Atomic Layer Epitaxy of III-N Semiconductors**, ***C.R. Eddy, Jr.***, U.S. Naval Research Laboratory, *N. Nepal,* American Association for Engineering Education, *N.A. Mahadik,* U.S. Naval Research Laboratory, *L.O. Nyakiti,* American Association for Engineering Education, *S.B. Qadri, M.J. Mehl, J.K. Hite*, U.S. Naval Research Laboratory

The synthesis of III-nitride semiconductors by atomic layer epitaxy (ALE) is explored to reveal that growth temperatures for high-quality crystalline layers are less than half that of conventional growth methods and that the new parameter space can lead to previously unrealized phases and stoichiometries of III-N binaries and ternaries.

ALE is a method in which the precursors for growth are introduced in a sequence of gas pulses added to an inert carrier gas flow at temperatures sufficient to promote either homo- or hetero-epitaxial growth. Here, we use alternating pulses of traditional group III metalorganics and plasma-activated nitrogen carried on an ultra-high purity argon carrier gas. A variety of substrates (silicon, sapphire, GaN templates on sapphire, etc.) are subjected to the pulse sequences at temperatures from 150°C to 500°C in a customized Cambridge Nanotech, Inc. Fiji plasma-assisted ALD reactor.

With proper surface preparations, high quality, wurtzitic AlN is grown at 500°C. These thin films (~36 nm) demonstrated smooth surfaces (~0.7 nm rms roughness for 10x10 $mm^2$ scan area) and a (0002) peak rocking curve width of 630 arc-sec [1,2], but contained a high fraction of carbon (8%) and small fraction of oxygen (0.6%). Similar results are demonstrated for GaN films grown between 350 and 450°C. For InN, two growth regimes were defined. One between 175 and 185°C, in which a new cubic phase of InN was realized, and a second regime between 220 and 260°C for which quality wurtzitic materials (262 arc-sec for (0002) reflection) were grown. As with AlN, both films contained high fractions of carbon (3%), but little-to-no oxygen (0.1%). Finally, initial efforts to grow ternaries of InAlN were conducted using a digital alloying approach where quality, crystalline ternaries were realized over the entire stoichiometric range. These early results suggest great potential for ALE growth of III-N semiconductors.

[1] T. Koyama et al., Phys. Stat. Sol. (a) 203, 1603 (2006). MBE (1.58 micron, 420 arc-sec).

[2] K. Balakrishnan et al., Phys. Stat. Sol. (c) 3, 1392 (2006). MOCVD (2 micron, 400 arc-sec).

10:20am **EM+NS+SS+TF-FrM7 Advances in Ternary Group III-Nitrides for Advanced Solid State Lighting, Photovoltaics and Thermoelectric Applications**, *B. Kuckgok, B. Wang, M. Orocz, A.G. Melton, N. Lu,* ***I.T. Ferguson***, University of North Carolina at Charlotte **INVITED**

The ternary group III-Nitrides have demonstrated great promise in becoming the universal III-V compound semiconductor material for electronic, optoelectronic and other applications. This talk will show that the III-Nitrides can provide a possible solution for many applications that traditionally used III-V materials and associated devices. The development of wide-band gap compound semiconductors materials and devices, in particularly III-Nitrides, are leading a revolution in energy related areas of light emitting diodes (LEDs) and, more recently, solar cells and thermoelectric applications. However, a sound understanding of the appropriate material properties of III-Nitride for these diverse applications is needed as well as the understanding the compromises that are needed in the corresponding device structures. For example, the use of LEDs in general illumination, known as solid state lighting, incorporate InGaN in such a way that it shows large compositional fluctuations in the active region of the device. This physical phenomenon has been associated with bright emission from these devices despite the high defect density in the material. Moreover, these first generation devices typically have poor color rendering capability, in addition to poor correlated color temperature associated with gaps in the power spectrum. The group III-Nitride technology is also the basis for the development of a new generation of highly efficient solar cells. Wide-band gap InGaN is one of the few materials that can provide bandgaps in the 2.4-2.9 eV range for multi-junction photovoltaics devices to achieve efficiencies greater than 50%. Single phase InGaN with indium compositions up to 30% (2.5 eV band gap) are needed for these applications including understanding their absorption characteristics and ability to p-type dope. Another emerging application for the group III-Nitrides is high temperature (>700°C) thermoelectric applications for waste heat harvesting. Recent measurements of the thermoelectric properties of InGaN; including the Seebeck coefficient, the electrical conductivity, and the power factor, etc., show promising results for this application. However, the effects of point and extended defects on thermoelectric properties, in particular the Seebeck coefficient, are not well understood and need further investigation.

11:00am **EM+NS+SS+TF-FrM9 InGaN Epilayer Growth using Migration-enhanced, Remote-Plasma MOCV**, *R.L. Samaraweera, F. Gueth, J.K.S. Nanayakkara, M.K.I. Senevirathna,* ***N. Dietz***, Georgia State University

Group III-nitrides possess a number of attractive physical, optical, and electronic properties that allow the fabrication of novel materials and device structures as presented in numerous reviews over the last two decades. However, encountered ternary and quaternary materials stabilization and integration problems under presently deployed processing conditions limit the indium incorporation to a narrow composition range. Potential pathways to stabilize group III-nitride alloys with higher indium content, include the pressure dependency of the surface chemistry, as well as kinetic stabilized growth concepts such as plasma-assisted MBE. Recent advances in remote-plasma-enhanced CVD and RF microwave plasma assisted MOCVD for the growth of group III-nitrides, demonstrate the epitaxial growth of InN and InGaN at growth temperatures of 450°C - 650°C with growth rates that are comparable to MOCVD.

In this contribution, we will present first results on epitaxial InGaN growth under migration-enhanced, remote-plasma MOCVD (MERP-MOCVD). The growth system is based on a rotating turbo-disc showerhead configuration with added provisions for the spatial and temporal control of plasma, metalorganic (MO) and hydride precursor injections, as well as real-time optical monitoring to study the evolution of surface chemistry processes as function of the process parameter. A remote plasma is generated by a nitrogen/hydrogen mixture injected in a hollow cathode, sustained by a 50W and 600W rf-power source. The reactive nitrogen species (e.g. $N^*/NH^*/H^*$ fragments) in the after glow regime of a remote plasma are directed to the growth surface using the after glow regime of the remote plasma.

Data will be presented and discussed for the GaN and InN process window as function of nitrogen/hydrogen plasma mixture, reactor pressure, substrate temperature, and rf-power setting. The layers have been characterized by x-ray diffraction (XRD), Raman spectroscopy, Fourier transform infrared (FTIR) reflectance and optical absorption spectroscopy.

11:20am **EM+NS+SS+TF-FrM10 The Growth and Structural Properties Analysis of Indium-rich InGaN Epilayers**, ***S. Gamage***, *J.K.S. Nanayakkara, M.K.I. Senevirathna*, Georgia State University, *A.G. Melton, I.T. Ferguson*, University of North Carolina at Charlotte, *N. Dietz*, Georgia State University

The large band gap tunability possible in ternary InGaN alloys opens new avenues in the field of advanced optoelectronics device structures. However, the stabilization of indium-rich InGaN epilayers is still a big challenge due large differences in the partial pressures and lattice parameters between the binaries InN and GaN, respectively. As a potential pathway to stabilize ternary InGaN alloys in a larger composition range and to reduce the temperature gap, we explore the growth of InGaN epilayers under super atmospheric pressures of up to 15 bars.

Starting from InN, we report in this contribution on the growth of indium-rich ternary $In_{1-x}Ga_xN$ epilayers (with $0 \leq x < 0.4$ ) and study the influence of the pulse separations on the phase purity and stability of indium-rich $In_{1-x}Ga_xN$ epilayer and resulting structural and optical layer properties. The structural InGaN epilayers are characterized by x-ray diffraction, Raman spectroscopy, and by infrared (IR) reflectance. The free carrier concentrations have been estimated by analyzing the IR-reflectance spectra and by Raman A1(LO) mode line shape analysis.

11:40am **EM+NS+SS+TF-FrM11 ALD Sidewall Passivation for Dark Current Reduction in GaN Avalanche Photodiodes**, ***J. Hennessy***, *L.D. Bell, S. Nikzad*, Jet Propulsion Laboratory, California Institute of Technology, *P. Suvarna, F. Shahedipour-Sandvik*, College of Nanoscale Science and Engineering, University at Albany

The detection of ultraviolet light has important applications in planetary imaging and spectroscopy, communications, and defense-related photosensing. One major challenge facing UV detection is visible-rejection, as UV photons in bands of interest are often greatly outnumbered by visible photons, effectively reducing the signal-to-noise ratio. Conventional systems for these detection applications include high-gain photomultiplier tubes and microchannel plate systems, which tend to be large, fragile, and require high-voltage operation. For these reasons, a more reliable all-solid-state alternative such as an avalanche photodiode (APD) is a desirable replacement option. III-N APDs based on the GaN/AlGaN material system are one candidate that can potentially offer high gain as well as visible-blind operation.

Significant materials challenges remain in order to improve the performance of AlGaN/GaN APDs, including the optimization of both bulk and surface defects. Sidewall-related defects in GaN APDs have often been observed to contribute to undesirable current components such as those produced by defect-related microplasmas. Although several approaches have been reported to address edge leakage issues, device repeatability and reliability remains a concern. In this work we investigate the effect of sidewall $Al_2O_3$ deposited by atomic layer deposition (ALD) as an alternative to more typical approaches like $SiO_2$ deposited by plasma-enhanced chemical vapor deposition (PECVD). ALD is an attractive option for III-N sidewall passivation due to the ease in depositing potentially more compatible materials with the AlGaN system, as well the ability to conformally coat three dimensional structures like mesa diodes.

The use of ALD $Al_2O_3$ as a sidewall passivation layer was observed to result in the reduced occurrence of premature breakdown in mesa p-i-n GaN APDs when compared to devices fabricated with a more common $SiO_2$ passivation deposited by PECVD. Mesa APDs with diameters ranging from 25 to 100 µm show a significant reduction in median dark current for the ALD-passivated devices. The reduction in median dark current was most significant for the smallest devices, showing an order of magnitude improvement at reverse biases near avalanche. The interfacial effect of ALD $Al_2O_3$ was investigated by fabricating MOS capacitors which show a large reduction in both slow trapping and faster interface states compared to PECVD $SiO_2$ devices.

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