Electronic Materials and Processing
Room: 210E - Session EM+MS-ThA

III-N Nitrides II
Moderator: Nikolaus Dietz, Georgia State University

2:20pm **EM+MS-ThA1 Accelerating Adoption of Wide Band Gap Semiconductors though Manufacturing Innovation**, ***John Muth***, North Carolina State University **INVITED**

As part of the national strategy for the United States to compete in the increasingly competitive global marketplace, a National Network for Manufacturing Innovation (NNMI) is being implemented to create a competitive and sustainable research-to-manufacturing infrastructure for U.S. Industry, academia and government to solve industry relevant problems.

PowerAmerica a $146 million dollar investment by the Department of Energy, Industry and the State of North Carolina is the second NMNI to be announced and with its industry and academic partners has initiated 20 projects focused on manufacturing wide band gap semiconductor devices and demonstrating their advantages in power electronic applications.

The mission of PowerAmerica is to develop advanced manufacturing processes to enable cost competitive, large-scale production of wide bandgap semiconductor-based power electronics, which allow electronic systems to be smaller, faster and more efficient than power electronics made from silicon. Innovations in manufacturing, improvements in reliability and demonstrations of system level advantages are important aspects of PowerAmerica's strategy to accelerate the adoption of wide band gap semiconductors into power electronics.

The number of systems that use power electronics between generation and use is about 20% today and is expected to grow to about 80% by 2030 a wide variety of technologies will be disrupted by the system advantages offered by wide band gap semiconductors. These include electric vehicles, motor drives, data centers, smart grid, photovoltaic and other renewable energy systems as well as niche applications in consumer electronics. In addition to the technical work performed in PowerAmerica a significant effort is being put towards workforce development and education. These efforts will prepare industry to compete in and the next generation of engineers and workers to lead the world into a brighter, more energy efficient world.

3:00pm **EM+MS-ThA3 InGaN/GaN Nanostructures for Efficient Light Emission and White Light Emitting Diodes**, *Y. Nakajima*, ***P. Daniel Dapkus***, *Y. Lin*, University of Southern California **INVITED**

InGaN/GaN quantum well LEDs that form the basis for efficient solid state lighting exhibit properties that limit the ultimate efficiency that can be achieved for this application. Among these deleterious properties are a high current efficiency decrease not related to heating – efficiency droop – and reduced efficiency in the green and yellow regions of the spectrum. It has been speculated that one of the causes for the droop and the reduced efficiency of green and yellow emitting diodes is the presence of piezoelectric fields that result from the growth of these structures on the polar (0001) plane of GaN.

In this work we report investigations of the formation of GaN nanostructures that are defined by non-polar and semi-polar planes that act as templates upon which quantum well active regions are formed. Nanorods, nanosheets, and nanostripe pyramids are described that are predominantly defined by {1-100}, {11-20}, and semi-polar planes and act as templates for the growth of InGaN/GaN multiple quantum well active regions. We describe the properties of blue LEDs formed on these templates and compare them to devices made on planar (0001) substrates.

Efficient green emitting LEDs and monolithic white light emitting LEDs require the extension of the range of efficient light emission in the InGaN / GaN materials system. We demonstrate high efficiency green and yellow light emitting multiple quantum well (MQW) structures grown on GaN nanostripe templates. The nanostripe dimensions range from 100 nm to 300 nm and have separations that range from 300 nm to 1 micron. Such small lateral dimensions are chosen to promote the elimination of threading dislocations from the structures. Nanostripes with various nonpolar and semi polar surfaces are grown with selective area growth on patterned c-plane GaN where the mask openings are oriented between the [10-10] and [11-20] directions. With stripes are aligned along the [10-10] and [11-20] directions, the sidewalls can be controlled to be nearly vertical or inclined and intersecting. Both shapes were examined and MQWs were grown on these different stripes. Photoluminescence (PL) measurement shows that MQWs grown on stripes with (10-11) surfaces and triangular shape emit the longest peak wavelength and have the best surface stability. Efficient PL emission peak wavelengths as long as 570 nm are realized on the triangular stripes with (10-11) surfaces by optimizing the MQW growth conditions for long wavelength emission. LED structures that utilize MQWs grown on nanostripes with (10-11) surfaces were fabricated to further demonstrate the viability of the approach.

4:00pm **EM+MS-ThA6 Tuning Bandgap Through Cation Ordering in New PV Materials**, ***Steve Durbin***, *R.A. Makin*, *N. Feldberg*, Western Michigan University, *J.P. Mathis*, *N. Senabulya*, *R. Clarke*, University of Michigan

There continues to be considerable interest in so-called earth abundant element compound semiconductors, of which we have multiple candidates at present. One material worth considering, $ZnSnN_2$, is properly termed a ternary heterovalent compound and is a member of the more general family of II-IV-V_2 semiconductors. It is analogous to InN, whereby pairs of indium atoms are replaced by a periodic arrangement of a Zn and Sn atom, and in that way is related to CIGS as that material corresponds to II-VI semiconductors. Although $ZnSnN_2$ is predicted to crystallize in an orthorhombic lattice with a bandgap of approximately 2.0 eV (calculations reported in the literature vary somewhat), we have observed that single crystal thin films grown by plasma-assisted molecular beam epitaxy are more likely to form in a wurtzitic lattice, with a lower electronic bandgap energy. In fact, we have recently observed both optical absorption and x-ray emission spectroscopy results on a series of films which agree with density functional theory calculations predicting a bandgap as small as 1 eV - the direct consequence of disorder in the cation sublattice. Careful tuning of the growth parameters enables the degree of order to be varied, and consequently the bandgap energy as well. This provides the intriguing possibility of tuning the bandgap through the growth process, as opposed to the traditional approach of alloying. The optimal bandgap energy of approximately 1.5 eV would therefore be an intermediate state between the two extremes.

4:20pm **EM+MS-ThA7 Comparison Studies of GaN Grown with Trimethylgallium and Triethylgallium for Optoelectronic Applications**, ***Mustafa Alevli***, Marmara University, Turkey, *A. Haider*, Bilkent University, Turkey, *N. Gungor*, Marmara University, Turkey, *S. Kizir*, *S. Alkis*, *A.K. Okyay*, *N. Biyikli*, Bilkent University, Turkey

Si is famous for the well-developed mature CMOS technology and a promising substrate for GaN due to its wafer size, low material cost, and possible integration with the CMOS. However, it is very difficult to deposit high-quality GaN films on Si due to its high deposition temperature which results in inter-diffusion at the GaN/Si interface and the relatively large lattice mismatch. Atomic layer deposition is a low temperature technique that can provide an alternative path for the deposition of GaN on Si.

In this study, GaN materials were grown at 200°C by two different kinds of metalorganic precursors, one by using trimethylgallium (TMG) and another by using triethylgallium (TEG) as gallium sources. It is reported that the carbon concentration was fifty times higher in the GaN films grown by TMG precursor than in that grown by TEG precursor. As it is going to be shown in this contribution, optical and electrical properties of Hollow cathode plasma-assisted atomic layer deposition of crystalline GaN films will be presented. When TMG pyrolyzes, it introduces more reactive CH_3 radicals in to the CVD reactor when it is compared to TEG precursor. It means that TMG enhances carbon incorporation in epitaxial film structure.

Spectroscopic ellipsometry studies on GaN films shows that refractive indices of GaN films increase when TMG was used as metalorganic precursor. The increase in the refractive index values indicates that the crystalline quality of GaN films improved with the use TMG. The change in the metalorganic precursor did not affect either the Bragg peak positions or crystalline phase of deposited GaN films. The grazing-incidence XRD patterns of both GaN films revealed that the films are polycrystalline with hexagonal wurtzite structure and are referring to (100), (101), (002), (102), (110), and (103) planes. The increase in the intensity and improvement in the FWHM value of the (002) peak also showed that the crystallinity improved for TMG grown GaN films. Further More,. The effect of alkyl precursors is also studied by a variety of characterization techniques Fourier Transform infrared reflectance, optical transmission, X-ray photoelectron spectroscopy, current-voltage characteristics of which the results will be discussed in detail.

This work is supported by TÜBİTAK project #114F002.

4:40pm **EM+MS-ThA8 Growth Control of InGaN Alloys and Nanostructures by Migration-Enhanced, Plasma-Assisted MOCVD**, ***Daniel Seidlitz**, I. Senevirathna, Y. Abate, N. Dietz,* Georgia State University, *A. Hoffmann*, Technical University Berlin, Germany

This contribution will present results of the structural and optoelectronic properties of InN and InGaN alloys and nanostructures as a function of temperature, reactor pressure and the temporal injection of metalorganic precursors and plasma activated nitrogen species (e.g. N*/NH*/NH_x*).

Migration-enhanced plasma-assisted metal organic chemical vapor deposition (MEPA-MOCVD) is utilized for the growth of InN and InGaN layers and nanocomposites at growth temperatures in the range of 450°C and 700°C. The custom-built MEPA-MOCVD system consists of a showerhead reactor combined with a hollow cathode (HC) plasma source (Meaglow) powered by a high-frequency (13.56 MHz) RF generator with a output power up to 600W. The HC plasma source creates reactive nitrogen fragments, which afterglow region approaches the growth surface. Plasma emission spectroscopy (PES) is utilized for real-time information about the formation and concentration of plasma generated active species. Added provisions allow a spatial and temporal injection of both, nitrogen and metalorganic precursors and enable the control of the epitaxial layers and their composition during the growth process.

Ex-situ investigations by Atomic Force Spectroscopy (AFM) as well as Fourier Transform Infrared Reflectance (FTIR) and Raman spectroscopy assess structural and optoelectronic properties (e.g. surface roughness, high-frequency dielectric constant e_∞, film thickness, etc.) of the deposited InN and InGaN nanostructures.

Correlation of the in-situ obtained plasma characteristics with the ex-situ results of the structural and optical properties of the InN and InGaN nanostructures are provided, as well as correlations between plasma afterglow regime position above the growth surface and the epitaxial layer properties. The aim of these studies is to access the phase stability regime of indium-rich ternary group III-nitrides as a function of growth temperature, kinetic energy of plasma species, reactor pressure, and temporal and spatial precursor supply.

5:00pm **EM+MS-ThA9 GaN on Rare-earth Oxide Buffer –A New Player in GaN-on-Si Technology**, ***Rytis Dargis**, A. Clark*, Translucent Inc.

We present the results of process development for GaN MOCVD epitaxial growth on Si using single crystal rare-earth oxide buffer layers. Advantage of this technological approach over traditional GaN-on-Si that uses a AlN nucleation buffer is the chemical isolation of the Si substrate from the group-III metals thereby preventing Si diffusion into the III-N layer. This removes one of the main breakdown failure modes being the silicon doped interface. Additionally, the relatively high breakdown electric field of rare-earth oxides (e.g. 4MV/cm for erbium oxide) can be used as part of the overall vertical breakdown thereby reducing the thickness of the III-N layer structure without impairment of electrical breakdown properties of a power device. This is important to the overall process since thinner GaN not only reduces MOCVD cycle time but results in lower stress in the structure. Additionally, thermal and chemical stability of the oxides opens up opportunity for implementation of a more flexible process for GaN-on-silicon including solutions used in GaN-on-sapphire.

Two types of the oxide buffers with thickness of 300 nm were grown of Si (111): single Er_2O_3 and double layer Er_2O_3-Sc_2O_3 structure were employed. Robustness and scalability of the oxide process make it suitable for manufacturing.

To validate the technology, the standard AlN-first process was used. GaN with thickness of 2 µm was grown in a state of the art 200mm manufacturing tool. It demonstrated excellent management of the stress in the structure with 25µm convex curvature, superior surface morphology (RMS = 0.56 nm, Z-range = 4.1 nm) and good crystal structure (GaN (002) FWHM = 561 arcsec, GaN (102) FWHM = 907 arcsec).

Our newly developed GaN-first MOCVD process, which is based on a typical GaN-on-sapphire process, uses nitridation and low temperature GaN buffer. During the growth, the upper part of the oxides is transformed into rare-earth nitride with lattice constant smaller than that of the oxide and consequently lower lattice mismatch to GaN (e.g. lattice constant mismatch between GaN and ScN is approximately -0.2%). The GaN layers with total thickness of 2.5 µm grown on the both types of the buffers exhibit smooth surface with RMS < 1 nm and Z-range <10 nm. The wafers exhibit good structural quality with X-ray diffraction GaN (002) peak FWHM of 540 arcsec and 684 arcsec for GaN on Er_2O_3 layer and Er_2O_3/Sc_2O_3 stack respectively. SIMS data shows no oxygen or rare-earth metal diffusion into the GaN.

5:20pm **EM+MS-ThA10 Plasma Enhanced Atomic Layer Deposition of Al_2O_3 on AlGaN/GaN High Electron Mobility Transistors**, ***Xiaoye Qin**, R.M. Wallace*, University of Texas at Dallas

Metal insulator semiconductor AlGaN/GaN high electron mobility transistors (MISHEMTs) are promising for power device applications due to a lower leakage current than the conventional Schottky AlGaN/GaN HEMTs. Among a large number of insulator materials, Al_2O_3 dielectric layer, deposited by atomic layer deposition (ALD), is often employed as the gate insulator because of a large band gap (and the resultant high conduction band offset on AlGaN)[1], high breakdown field, conformal growth, and a relatively high dielectric constant. However, the thermal ALD Al_2O_3 does not passivate the surface effectively according to our previous work.[1–4] In this work, the half cycle study of plasma enhanced atomic layer deposited (PEALD) Al_2O_3 on AlGaN is investigated using *in situ* X-ray photoelectron spectroscopy (XPS), low energy ion scattering (LEIS) and *ex situ* electrical characterizations. A faster nucleation or growth is detected in PEALD than thermal ALD using an H_2O precursor. The PEALD Al_2O_3 layer decreases the gate leakage current as the ALD Al_2O_3. Importantly, the remote O_2 plasma oxidizes the AlGaN surface slightly at the initial stage, which passivates the surface and reduces the OFF-state leakage. This work demonstrates that PEALD is a useful strategy for Al_2O_3 growth on AlGaN/GaN devices.

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Reference

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