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

III-N Nitrides for Optoelectronic Applications
Moderator: Rachael Myers-Ward, U.S. Naval Research Laboratory, Aubrey Hanbicki, U.S. Naval Research Laboratory

8:00am **EM+MS-ThM1 Hollow Cathode Plasma-Assisted Atomic Layer Deposition of Wurtzite InN and $In_xGa_{1-x}N$ Thin Films with Low Impurity Content**, ***Ali Haider***, *S. Kizir, C. Ozgit-Akgun, E. Goldenberg, M. Alevli, A. Kemal Okyay, N. Biyikli*, Bilkent University, Turkey

Among the III-nitride compound semiconductor family, InN is known with its unique properties which are crucial for both electronic and optoelectronic applications such as narrow band gap, small effective mass, and high electron mobility. Since InN and its alloys are currently the backbone of LED industry for bandgap tuning and are mostly grown using high-temperature epitaxy, experimental efforts on enabling low-temperature growth are critical to widen its perspective for applications like flexible (opto)electronics. In addition, a growth method in which indium composition can be precisely controlled for $In_xGa_{1-x}N$ alloys is highly imperative for band gap engineering.

In this work, we summarize our recent progress on the development of crystalline InN and $In_xGa_{1-x}N$ thin films with low impurity content at a substrate temperature as low as 200 °C by hollow cathode plasma-assisted ALD (HCPA-ALD). Deposition of polycrystalline wurtzite InN thin films was achieved using trimethylindium ($InMe_3$) and N_2 plasma sources. Process parameters including $InMe_3$ pulse time, N_2 flow rate and duration, purge time, deposition temperature, and plasma power were investigated. Detailed structural and optical characterizations of InN and $In_xGa_{1-x}N$ were performed. N_2 plasma exposure time had a profound effect on the impurity content of the InN films. After saturating the surface of substrate with $InMe_3$ molecules, the ligands of $InMe_3$ were removed completely only after sufficient exposure dose of N_2 plasma. Insufficient exposure times of N_2 plasma resulted in InN films with higher carbon impurity contents as determined from XPS measurements, which were arising from methyl ligands of $InMe_3$. After optimizing the precursor dosages,XPS survey scan obtained from the bulk part of the InN film showed that *h*-InN films were carbon and oxygen free. On the other hand, indium composition in different $In_xGa_{1-x}N$ thin films was determined by energy-dispersive X-ray spectroscopy, X-ray photoelectron spectroscopy, and X- ray diffraction. GIXRD measurements revealed the hexagonal wurtzite crystalline structure of the grown InN and $In_xGa_{1-x}N$ thin films. Refractive index of the InN film at 750 nm was estimated to be 2.67 while refractive indices of $In_xGa_{1-x}N$ thin films increased from 2.28 to 2.42 at wavelength of 650 nm with increase in indium composition. Optical band edge studies of the $In_xGa_{1-x}N$ films confirmed the successful tunability of the optical band-edge with alloy composition. Our results show that HCPA-ALD is an alternative technique to grow crystalline InN and $In_xGa_{1-x}N$ films at low substrate temperatures.

8:20am **EM+MS-ThM2 Infrared Nanoscopy of Indium-rich InGaN Epilayers**, ***Yohannes Abate***, *D. Seidlitz, N. Dietz*, Georgia State University, *I. Ferguson*, Missouri University of Science and Technology

The unique optical and electrical properties of ternary $In_{1-x}Ga_xN$ epilayers and heterostructures therewith makes this material system attractive for various optoelectronic device applications, including but not limited to high-speed electronics, frequency agile photovoltaic solar cells, or light emitting devices. However, the presently utilized growth methods enable the indium incorporation in $In_{1-x}Ga_xN$ heterostructures to a narrow composition range, before phase instabilities are encountered. As a potential pathway to extend the stable composition range and the control of point defects in the alloys, we explored in recent years the reactor pressure dependency under superatmospheric MOCVD - also denoted high-pressure chemical vapor deposition (HPCVD) - conditions. In this contribution we will report and discuss on the growth of indium-rich ternary $In_{1-x}Ga_xN$ epilayers and 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 properties. The InGaN epilayers have been characterized by x-ray diffraction, Raman spectroscopy, atomic force microscopy, and by several optical techniques such as infrared (IR) reflectance and optical absorption spectroscopy. The free carrier concentrations have been estimated by analyzing the IR-reflectance spectra and by Raman A1(LO) mode line shape analysis.

8:40am **EM+MS-ThM3 Surface Treatment and Characterization of InN (0001)**, *S.P. Park, T. Kaufman-Osborn, K. Sardashti*, University of California San Diego, *S.M. Islam, D. Jena*, University of Notre Dame, ***Hyunwoong Kim***, *A.C. Kummel*, University of California San Diego

Indium nitride (InN) is a promising material due to the its band offset to GaN. However, employing InN in practical devices is still challenging because it has an electron accumulation at the surface which is hypothesized to be due to an In-In double layer at the surface. For practical InN devices, it is critical to remove this In-In double layer and form a non-metallic surface. This work describes the transformation of the atomic order, elemental composition, and electric structure of InN (0001) surface during the removal of the metallic layer and its replacement with gate oxide using scanning tunneling microscopy (STM), x-ray photoelectron spectroscopy (XPS), and scanning tunneling spectroscopy (STS). Three cleaning methods were studied. (1) Ex -situ wet cleaning was performed by using HCl, NH OH, and (NH) S solution to remove native oxide. STM showed the surface is smooth and uniform and STS showed n-type conductivity with a band gap of 0.7 eV consistent with strong intrinsic accumulation of electrons on the surface. (2) In-situ atomic hydrogen cleaning on wet cleaned InN surface was performed. However, due to the preferential nitrogen depletion in atomic hydrogen cleaning, the ratio of indium to nitrogen was increased. STM images showed rows of indium dimers, and STS showed that there was a metallic zero band gap surface, consistent with an In-In double layer surface termination. (3) As an alternative method to eliminate the accumulation of electron at InN surface, an O passivation was performed on wet cleaned InN. The O exposed surface was atomically flat and uniform. STM line traces showed islands were formed with step height of 3.5 angstrom consistent with formation of an O-In-O layer. The band gap of the O passivated InN surface was 0.8 eV and the Fermi level was midgap consistent with absence of In-In double layer.ALD nucleation was studied using TMA pre-dosing and an additional 10 cycles of TMA and H_2O doses on an O_2 passivated InN substrate. After the 10 cycles of ALD, the ratio of Al to O ratio was 2:3 consistent with the stoichiometric ratio of Al_2O_3, The ALD process broadened the band gap from 0.8 eV to 1 eV due to the formation of Al-O-Al bonding, In sum, an unpinned non-metallic surface without the formation of In-In layer was achieved on InN using an oxidant and cyclic dose of TMA and water.

9:00am **EM+MS-ThM4 State-Of-The-Art High Efficiency Thermoelectric Material: III-Nitrides as a Wide Bandgap Semiconductor**, *B. Kucukgok, N. Lu*, University of North Carolina at Charlotte, ***Nikolaus Dietz***, Georgia State University, *I. Ferguson*, Missouri University of Science and Technology

Thermoelectric (TE) devices have gained widespread interest as a renewable energy source in the field of energy conservation and emission reduction due to their direct conversion of heat into electricity by Seebeck effect of TE materials. Additionally, TE devices have been used in wide variety of applications, due to their reliability, stability, and low-cost, such as automotive industry, spacecraft radioisotope power supply, and photovoltaic solar cells. Since TE device performance is directly related to material efficiency, material selection becomes essential. Recently, the interest of potential applications of III-nitride semiconductors in the TE field has been initiated due to their distinguished features including high-temperature operation, high mechanical strength, and large-band gap range and their promising TE figures of merit (*ZT*), mostly for materials based on AlGaN and InGaN alloys. Here, we demonstrate the room temperature thermoelectric properties of III-nitrides such as GaN and its alloys, grown by metalorganic chemical vapor deposition (MOCVD). The structural, optical, electrical, and thermal properties of the samples were examined by X-ray diffraction, photoluminescence, van der Pauw hall-effect, and thermal gradient methods, respectively. The objectives of this paper are to understand the role of defects, carrier density *n*, and composition *x* on the TE properties of III-nitrides.

9:20am **EM+MS-ThM5 Nanofabrication of Advanced Nanophotonic Structures by Nanoimprinting**, ***Stefano Cabrini***, Lawrence Berkeley National Laboratory (LBNL) **INVITED**

To exploit the potentialities of Nanophotonics, it is important to control the properties of the material at the nanometer scale, obtaining a good agreement between the experiments and the theory. Nanofabrication can open the way for new concept of devices. In this presentation we will present the fabrication and characterization of simple photonic crystals directly pattern by nanoimprinting using a special functional resist with high refractive index.

11:00am **EM+MS-ThM10 Advanced III-Nitride Device for RF Switch Applications: A Record 2THz Fco Super-Lattice Castellated Field Effect Transistor (SLCFET) for Low Loss RF Switching**, ***Shalini Gupta***, *R. Howell, E. Stewart, J. Parke, B. Nechay, M. King, H. Cramer, J. Hartman, R. Freitag, M. Snook, I. Wathuthanthri, G. Henry, K. Renaldo*, Northrop Grumman ES **INVITED**

Northrop Grumman Electronic Systems (NGES) reports on the development of a novel field effect transistor structure, based on a super-lattice epitaxial layer combined with a three dimensional castellated gate structure to achieve a 3x improvement in RF switch figure of merit compared to current state of the art transistor technologies. RF switch components are vital for the successful implementation of a variety of system architectures, spanning applications from phased array radars to the wireless components of mobile phones and consumer electronics.

NGES used MOCVD growth techniques to grow a GaN/AlGaN based super-lattice on a 100 mm diameter semi-insulating SiC substrate which is used as the SLCFET conductive channel. This super-lattice creates multiple 2DEGs producing parallel current channels between the source and drain of the device resulting in currents several times higher than conventional FETs and a record low GaN epi sheet resistance of 60 ohm/sq. The low epi sheet resistance in turn reduces the on resistance of the FET which results in a low insertion loss RF switch. Although super-lattice structures have been employed to make optoelectronic semiconductor devices, their use in FETs have been limited due to difficulty in pinching-off the stacked paralleled current channels. This is because the top channels screen the bottom channels from the electric field of the gate thereby increasing the voltage needed to pinch off the channel and turn off the device to a value beyond the breakdown field of the semiconductor. The SLCFET overcomes this challenge by employing a side-pinching gate. This is realized by etching features in the semiconductor prior to a 0.25 um gate deposition which allows the gate metal to surround the channels on the top and sides. This feature resembles the crenellations of a castle and hence is called a castellated gate.

Electrical measurements of the SLCFET transistor reveal a high I_{MAX} of 2.7 A/mm and a pinch off voltage of -8V. The SLCFET has a low on resistance (R_{ON}) of 0.4 Ohm-mm and an off capacitance (C_{OFF}) of 0.2 pF/mm, resulting in an RF switch figure of merit ($Fco = 1/2\pi R_{ON}C_{OFF}$) of 2 THz, 3x higher than the current state of the art FET based RF switches. SLCFET MMICs have been designed and tested including Single Pole Double Throw (SPDT) switches, tunable filters, and true time delay units. State of the art electrical results have been obtained, such as a series-shunt broadband (1-18 GHz) SLCFET SPDT with a measured insertion loss of 0.25 dB at 10 GHz, with -35 dB of isolation and -23 dB of return loss. These state-of-the-art results demonstrate that SLCFET is an enabling technology for next generation RF systems.

11:40am **EM+MS-ThM12 Developing Periodically Oriented Gallium Nitride for Frequency Conversion**, ***Jennifer Hite***, *R. Goswami, J.A. Freitas, M.A. Mastro, I. Vurgaftman, J.R. Meyer,* U.S. Naval Research Laboratory, *C.G. Brown,* University Research Foundation, *F.J. Kub, S.R. Bowman, C.R. Eddy, Jr.*, U.S. Naval Research Laboratory

Gallium nitride is a semiconductor widely used in both optical and electronic devices. The polarity of GaN (+/- c-direction) influences many properties of the resultant material, including chemical reactivity and electric field in these 'spontaneously polarized' materials. By engineering inversion layers, we have demonstrated control of GaN polarity on both polar faces of GaN. By employing a selective growth method to deposit the IL, the lateral polarity of the GaN can be alternated, thus enabling structures referred to as periodically oriented (PO) GaN.

On N-polar substrates, we demonstrated that optimization of the MOCVD growth rates resulted in sharp, vertical interfaces and smooth surfaces. This work has moved the technology substantially closer to practical non-linear optic emitters by using HVPE to extend the PO GaN templates on N-polar substrates to total thicknesses of up to 500 mm, while faithfully maintaining the pattern of alternating polarity. Additionally, cross-sectional cathode-luminescence (CL) imaging of such an extension shows that the large initial dislocation densities occurring in the original inversion layers greatly decreased after about 25 µm of regrowth.

For growth on Ga-polar substrates, we have demonstrated that inversion layers can be created using atomic layer deposition (ALD) of Al_2O_3. This new capability is especially relevant because Ga-polar films are more prominent in devices, as they result in lower impurities, higher quality and smoother films. In this case, GaN grown over the inversion layer is N-polar. This inversion layer was used to form laterally-patterned stripes of alternating Ga- and N-polar films. We find that annealing the ALD films crystallizes the Al_2O_3, thereby allowing N-polar GaN to be grown over the new sapphire-like surface. Transmission electron microscopy shows that the inversion layer in a PO GaN structure is crystalline, a-plane oriented, and a-phase. TEM characterization further indicates that the GaN layers, both above and below the Al_2O_3 inversion layer, are c-oriented without any rotation between them. The optimization of this process has enhanced the surface smoothness. The latest results in demonstrating secondary harmonic generation will be presented.

These methods of GaN polarity inversion offer the promise of engineered materials with custom lateral and vertical polarity variations for applications in novel electronic and optoelectronic devices, a subset of which are expected to be suitable for non-linear optics.

12:00pm **EM+MS-ThM13 Electronic and Optical Device Applications based on III-Nitride Films Grown by Plasma-Assisted ALD**, *B. Tekcan,* ***Sami Bolat***, *C. Ozgit-Akgun, N. Biyikli, A.K. Okyay*, Bilkent University, Turkey

For many electronic and optical applications, III-nitride materials are much sought after due to their direct and high optical band-gap, high electron saturation velocity and band-gap tunability [1]. These important features enable many possible device applications, which are generally used in high power and high frequency applications [2]. However, these films are generally grown using high temperature and high vacuum processes namely, MOCVD [3], MBE [4] which limit substrate selection along with CMOS compatibility. In our work, we offer an alternative way of growth to fabricate thin film transistors (TFTs) and UV metal-semiconductor-metal (MSM) photodetectors. Hollow cathode plasma assisted Atomic Layer Deposition (HC-PA-ALD) technique make low temperature device applications possible. We have grown GaN and InGaN films and analyzed TFT and photodetector properties in detail. Electrical and optical characteristics of these devices are inspected.

The results can pave the way for ALD to be used for III-Nitride based electronic and optical devices. Thin film transistor exhibit $2x10^3$ ON/OFF ratio with threshold voltage of 11.8 V. Metal-semiconductor-metal (MSM) photodetectors, on the other hand, showed 20 pA under -20 V voltage bias with a UV responsivity of 680 m A/W under 290 nm incident light with only a 20 nm thick film. Effect of annealing on the device performance is also studied. TFTs ON/OFF ratio increased to $2x10^4$ with a lower threshold voltage and contact resistance decreased 4000 times when annealed at 800 °C for 30 seconds. Moreover, MSM devices performance also enhanced after annealing 600 °C. The photoresponsivity as high as 950 m A/W at 290 nm incident light is recorded. The dark current reduced significantly, a current value of 50 fA is recorded under -20 V voltage bias.

Along with GaN devices, InGaN based photodetectors are fabricated and characterized. MSM devices based on InGaN devices showed responsivity and dark current levels controlled by In concentration. The resistivity of the films decreased with concentration of In in the semiconductor. Changing the In concentration, bandgap tunability is possible.

References:

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