Electronic Materials and Processing Division
Room: 209 - Session EM1-MoA

Group III-Nitrides and Hybrid Devices
Moderator: K. Kavanagh, Simon Fraser University, L. Porter, Carnegie Mellon University

2:00pm **EM1-MoA1 Electrically-Monitored Gate-Recess for Normally-Off AlGaN/GaN High-Electron Mobility Transistors**, ***H. Kim***, *M. Schuette, W. Lu*, The Ohio State University

GaN-based power devices have been intensively investigated for high power switching applications as well as high power microwave applications. Particularly, high breakdown voltage and high saturation velocity of GaN-based heterostructures facilitate reduction in on-state loss and switching loss compared to currently dominant Si-based power devices. Moreover, normally-off GaN-based power field-effect transistors (FETs) offer their inherent safety, reduced power consumption, and diverse circuit functionality with normally-on ones. Recently, we developed a zero-bias Cl-based dry etching process to thin AlGaN barrier with a minimal damage for enhancement-mode AlGaN/GaN FETs. However, it has been difficult to control gate-recess process for normally-off GaN-based FETs due to strong polarization effects. Namely, 1 nm under- or over-etchings near the critical AlGaN barrier thickness where the channel is pinch-off result in a negative threshold voltage (V_T) or a degraded transconductance (G_m), respectively. In this work, we report a methodology to control our Cl-based gate-recess for both positive V_T and high $G_{m,MAX}$ by relating electrical properties of the gate-recessed area before gate metallization to V_T and G_m in AlGaN/GaN FETs.

Gate-recessed AlGaN/GaN FETs were fabricated through fast etching with BCl_3 and slow etching with Cl_2/N_2/10%-O_2 to thin AlGaN barrier. The slow etching runs under inductively-coupled plasma mode only to minimize the damage. For monitoring purpose, resistance at 0 V (R_{0V}) and drain-to-source current ($I_{D,SAT}$) at 10 V between source and drain contacts were measured before gate metallization to correlate with V_T and G_m after gate metal deposition.

I_D-V_{GS}, G_m-V_{GS}, and capacitance-voltage characteristics of gate-recessed FETs with different AlGaN thicknesses by doing Cl_2/N_2/10%-O_2 etching for different times were measured and V_T values were extracted by linear extrapolation at $G_{m,MAX}$. V_T and $G_{m,MAX}$ were correlated with the monitoring parameters of R_{0V} or $I_{D,SAT}$. V_T and $G_{m,MAX}$ distributions with R_{0V} or $I_{D,SAT}$ guide us for monitoring as well as design of gate-recess process. For example, a recessed FET showing R_{0V} = 1700 W with 7 nm AlGaN barrier exhibits V_T of 0.56 V and $G_{m,MAX}$ of 300 mS/mm. In addition, our recess process offers sufficiently long monitoring time (at least 4 minutes) to tune the gate recess for target V_T together with high $G_{m,MAX}$. Based on the distribution, the necessity of tuning process is determined and its progress is monitored by R_{0V} or $I_{D,SAT}$ before gate metallization until target R_{0V} or $I_{D,SAT}$ is met. Our electrically monitoring method allows gate recess process to be well-controlled for target V_T and $G_{m,MAX}$.

2:20pm **EM1-MoA2 Atom Probe Tomography Studies on Green Light Emitting InGaN/GaN Multi Quantum Wells Grown on GaN Substrates**, ***F. Liu***, *L. Huang,* Carnegie Mellon University, *S.V.N.T. Kuchibhatla, D.K. Schreiber,* Pacific Northwest National Laboratory, *M. Zhang,* University of Michigan, *E.A. Preble, T. Paskova, K.R. Evans,* Kyma Technologies, Inc., *L. Porter, R.F. Davis*, Carnegie Mellon University

Carrier *delocalization* in InGaN/GaN multi-quantum wells (MQW) contained within green light-emitting diodes (LEDs) has been proposed as a contributor to LED efficiency droop. By contrast, interface roughness and fluctuations in composition within the MQWs may act to localize and confine carriers[1]. In this study, InGaN/GaN MQWs were grown on both (0001)GaN layers and on $In_xGa_{1-x}N$ buffer layer with graded In mole frations from 0 to 10%. Both heterostructures were grown on chemomechanically polished (0001)GaN substrates. Calculations using temperature-dependent photoluminescence spectra revealed a four-fold increase in the internal quantum efficiency (IQE) in the latter structure. A LEAP 4000X HR^{TM} pulsed UV laser (355 nm at 200 kHz) atom probe tomograph was used to investigate the elemental and spatial characteristics of the interface of the $In_xGa_{1-x}N$/GaN MQWs. To establish consistent atom probe operation parameters for reliable comparison among different samples, a systematic study was conducted to optimize the evaporation rate and laser energy. The concentration profile of $In_xGa_{1-x}N$/GaN MQW showed slightly varied In fraction among different QWs, ranging from x=0.21 to x=0.27, while the XRD results showed an average In fraction in all QWs of x=0.25. Furthermore, based on isoconcentration surface analysis and proximity histograms the upper surfaces of InGaN QWs appear to be more diffuse than the lower surfaces. These results indicate surface roughening of the InGaN layer. A detailed comparison of the two structures will be presented and the ability of 3-D atom probe tomography for such an analysis and the impact of the results on next generation LED technologies will be discussed.

1. J. Hader, J. V. Moloney and S. W. Koch, Appl. Phys. Lett. **96** (22), 221106 (2010).

2:40pm **EM1-MoA3 Local Surface Electrical Characterization of Polar GaN Surfaces**, ***J.D. Ferguson***, *M.A. Reshchikov, A.A. Baski*, Virginia Commonwealth University

While GaN is a widely-used material in optoelectronic devices, localized surface-related electrical properties are not well-understood. These properties affect the operational performance and lifetimes of GaN-based devices. Here, several atomic force microscopy (AFM) techniques were used to characterize the Ga-polar, +c [0001], and N-polar, -c [0001bar], surfaces of free-standing bulk GaN. Samples were prepared by either a chemical-mechanical polish (CMP) or mechanical polish (MP) of HVPE-grown GaN. AFM data showed that the Ga-polar surfaces (MP and CMP) were uniformly flat with rms roughness of less than 1 nm over a 5x5 micron image. In contrast, the N-polar surfaces were significantly rougher (~5 nm rms) with scratch-like features (100 nm wide, microns long), where the CMP treatment resulted in the presence of surface protrusions (~100 nm dia.) in proximity of the scratches. We then examined the local electrical properties using conducting AFM (C-AFM) to map surface conductivity and to obtain I-V spectra. C-AFM images at forward-bias (<6V) showed small contrast variations for all samples except the N-polar CMP surface. In that case, we observed less conducting behavior on the protrusions as compared to the surrounding surface. Local I-V data also revealed a higher forward-bias, turn-on voltage for the N-polar vs. Ga-polar samples. To investigate the local surface charging behavior, we used a two-step technique. First, a metallized AFM tip was used to locally charge the surface by applying a DC voltage, and then the resulting change in surface potential was monitored as a function of time with scanning Kelvin probe microscopy (SKPM). These surface charging data showed a smaller change in surface potential for the N- vs. Ga-polar samples, which appears to be consistent with the lower onset of conduction for the N-polar orientation. Finally, we measureed the photo-induced changes in surface potential under UV light exposure (100W Hg lamp), otherwise known as the surface photovoltage effect (SPV). The N-polar samples had a smaller SPV compared to Ga-polar, which indicates a smaller amount of band bending at the surface. Additionally, N-polar GaN restored to dark-state conditions at a much faster rate, regardless of CMP or MP treatment. In summary, we observed differences in morphology and electrical behavior for the two polar, c-plane GaN surfaces, as well as differences in behavior due to CMP and MP treatments. These data suggest a less pronounced surface charging behavior on N-polar vs. Ga-polar GaN.

3:00pm **EM1-MoA4 The Effect of Ammonia - TMI Pulse Separation on the Structural Properties of InN Epilayers**, ***R. Atalay***, Georgia State University, *M. Buegler,* Technische Universität Berlin, Germany, *S. Gamage, I. Senevirathna, A.G.U. Perera,* Georgia State University, *J.S. Tweedie, R. Collazo,* North Carolina State University, *N. Dietz*, Georgia State University

Over the last decade, significant research efforts have been devoted to understand and improve the properties of InN epilayers. However, even today, there is a significant lack of on understanding of the InN surface and growth chemistry and its affect on the physical bulk properties. Crucial challenges in the growth of InN epilayers are the vast different partial pressures between indium and nitrogen and associated fragments of the utilized precursors trimethylindium (TMI) and ammonia (NH3).

In this work, high-pressure chemical vapor deposition (HPCVD) is employed and explored in order to control and suppress the disassociation of InN alloys at higher growth temperatures. In order to reduce gas phase reactions and to control the surface chemistry, a pulsed precursor injection approach has been implemented, which provides additional process control parameters for the optimization of the physical epilayers properties.

In the pulsed precursor injection approach, the precursor separation times between the metal organic (MO) sources (TMI and TMG) and ammonia (S1), and ammonia and MO (S2) are two critical process parameters.

This contribution will present results on how the precursor separation times between the TMI and ammonia (S1) and ammonia and TMI (S2) affect the structural and optical properties of InN epilayers grown on GaN/sapphire

templates and/or sapphire substrates. In this study, the separation times S1 and S2 have been varied from 1000 to 2500 ms and 250 to 500 ms, respectively. The results show that a longer S1 separation of around 1700 ms and short S2 separation of around 360 ms provide the best structural properties of InN epilayers.

The InN epilayers have been analyzed by Raman scattering, X-ray diffraction, IR reflection, and transmission spectroscopy. The Raman studies showed that the lowest FWHM of E2(high) vibrational mode with about 8 cm-1 for a S2 separation time of 358 ms. XRD 2Θ-ω scans on these InN epilayers and the analysis of the InN (0002) Bragg reflex confirm the improved structural properties for the optimized S2 separation.

3:40pm **EM1-MoA6 Neutron Scattering Provides a New Model for Optimal Morphologies in Organic Photovoltaics: Rivers and Streams**, ***M. Dadmun***, *W. Yin*, University of Tennessee, *J. Ankner*, *K. Xiao*, Oak Ridge National Laboratory

Organic Photovoltaics (OPVs) have attracted increasing interest as a lightweight, low-cost and easy to process replacement for inorganic solar cells. Moreover, the morphology of the OPV active layer is crucial to its performance, where a bicontinuous, interconnected, phase-separated morphology of pure electron donor and acceptor phases is currently believed to be optimal. In this work, we use neutron scattering to investigate the morphology of a model OPV conjugated polymer bulk heterojunction, poly[3-hexylthiophene] (P3HT) and surface-functionalized fullerene 1-(3-methyloxycarbonyl) propy(1-phenyl [6,6]) C_{61} (PCBM). These results show that P3HT and PCBM form a homogeneous structure containing crystalline P3HT and an amorphous P3HT/PCBM matrix, up to *ca.* 20 vol% PCBM. At 50 vol% PCBM, the samples exhibit a complex structure containing at least P3HT crystals, PCBM crystals, and a homogeneous mixture of the two. The 20 vol% PCBM samples exhibit behavior consistent with the onset of phase separation after 6 hours of thermal annealing at 150 °C, but appears to be miscible at shorter annealing times. This suggests that the miscibility limit of PCBM in P3HT is near 20%. Moreover, for the 50 vol% PCBM sample, the interface roughens under thermal annealing possibly owing to the growth of PCBM crystals. These observations suggest a different morphology than is commonly presented in the literature for optimal bulk heterojunctions. We propose a novel 'rivers and streams' morphology to describe this system, which is consistent with these scattering results and previously reported photovoltaic functionality of P3HT/PCBM bulk heterojunctions.

4:20pm **EM1-MoA8 Novel Boron Carbide-Based Semiconducting Polymers for Enhanced Electronic Properties**, ***F. Pasquale***, *J. Kelber*, University of North Texas

We report the controlled modification of valence band electronic structure of semiconducting boron carbides with sharply narrowed band gap, by combination of 1,4 diaminobenzene (DAB) with orthocarboranes to form a novel boron-carbide based semiconducting film. Semiconducting boron carbide films ($B_{10}C_2H_x$) and related materials formed from crosslinking of carborane icosahedra are of rapidly increasing interest in neutron detection, nanoelectronics, spintronics, and even conventional CMOS ULSI applications. The ability to modify the material's electronic structure in a controlled manner is of obvious interest in all these areas. We report x-ray and ultraviolet photoelectron spectra (XPS, UPS), demonstrating that electron-induced cross-linking of carborane and DAB results in a novel semiconductor with a significantly enhanced valence band density of states near the Fermi level, resulting in a shift, as determined by UPS, in the valence band maximum from ~ 4.3 eV to ~ 1.7 eV below the Fermi level. Importantly, this effect is relatively insensitive to total film thickness and for DAB/orthocarborane atomic ratios (determined by XPS) ranging from 1:4 to 1:1. Films were formed by condensation and cross-linking of alternating layers of orthocarborane and DAB precursors under ultrahigh vacuum (UHV) conditions, allowing precise control of relative DAB and carborane concentrations. This procedure also yielded films of systematically varied DAB/carborane concentration and film thicknesses between 20 Å and 100 Å average thickness, as determined by attenuation of $Cu(2p_{3/2})$ photoemission intensity from the substrate. The films exhibited shifts in the valence band spectra of ~ 0.2 eV to lower binding energies upon cross-linking, indicating a surface photovoltage effect, and the formation of a true *p*-type semiconducting film. The results demonstrate formation of a new semiconducting material based on carborane icosahedra but modified by the addition of an organic species. These data further indicate the potential for the development of a broad range of novel boron carbide-based polymers using carboranes and other organic additives, with film formation by a variety of methods, including photon or electron bombardment, or plasma-enhanced chemical vapor deposition.

4:40pm **EM1-MoA9 Analysis and Application of Hybrid Electronic Structures Formed by Nanoscale Conductive Coatings on Textiles**, ***J.S. Jur***, *W. Sweet, C.J. Oldham, G.N. Parsons*, North Carolina State University

Electronic functionalization of complex fibrous systems is of interest for developing new hybrid electronic systems geared toward integrating biological detection and energy harvesting devices in textile materials. Reliable methods to evaluate the electrical properties of these textiles are necessary for future device design and performance improvement. This work investigates conformal, nanoscale coatings of zinc oxide and tungsten produced by atomic layer deposition (ALD) on natural and synthetic fibers structures, resulting in novel hybrid-based electronic structures. A modified 4-probe test method is introduced to evaluate the effective conductivity of these coatings. An applied normal force orthogonal to the current and field direction improves the fiber/fiber contact, resulting in consistent evaluation of the effective conductivity of the coatings across fiber systems and is a unique method of evaluating the mechanical behavior of these coated fiber structures. Optimization of the coatings has resulted in conductivity values as high as 40 S cm^{-1} for zinc oxide coatings (~75 nm) on polypropylene and cotton fiber, as well as 1150 S cm^{-1} for ALD tungsten (~50 nm) on quartz fiber matrices. Device application of these coated fiber matrices are benefited by their "all-fiber" structure, with characteristic high porosity and surface area. For example, a textile-based flow-through metal-insulator-metal capacitors fabricated from tungsten-coated quartz fibers is shown as an application in liquid chemical sensing. The mechanisms related to electron transport in a surface-coated textile fabric and implications on device fabrication and improvement will be discussed.

5:00pm **EM1-MoA10 Quantum Dot Transfer using Patterned Self-Assembled Monolayers**, ***S. Miller***, *A.J. Muscat*, University of Arizona

Nano particles such as light emitting quantum dots offer many exiting new possibilities for device manufacturing. Along with the potential for low cost manufacturing, the ability to make quantum dot based solar cells and LEDs, has lead to the potential to make arrays of light detectors and nanometer scale patterned LEDs. Using two such devices together results in an optical switch, which may be employed in computer processing as a fast memory readout device. In addition ROM memories can be created using direct patterning of light emitting quantum dots on a disk. Because quantum dots of different size emit different wavelengths it is possible to code data in several wavelengths allowing the data from each wavelength to be written in the size limited area of focused light, dramatically increasing data storage. Many of the potential devices which can be made using nano particles require precise control over nano particle placement and layer thickness. We have found that it is possible to control quantum dot placement using a patterned self-assembled monolayer (SAM). Due to the hydrophobic properties of octadecyltrichlorosilane (OTS) it is possible to form an OTS SAM on which quantum dots will not deposit. This SAM layer can then be patterned using one of several methods. One approach is to use direct UV light exposure in air through a shadow mask, this will remove the OTS SAM in the open areas of the mask, allowing for quantum dot deposition to occur only in the open areas. OTS SAMs can also be formed on pre-made chemical patterns. Ultra high resolution patterns can be formed using nano-lithography including conductive atomic force microscopy, STM, and EBL. Arrays of conductive atomic force microscope tips can be used to pattern repeated patterns such as those required for detectors. Quantum dots or an alternate SAM can then be deposited directly into the open pattern areas. However, because of the time required for nano-lithography, it is desirable to use the patterned OTS SAM as a nano particle master stamp, where the quantum dots are transferred from the patterned OTS surface to a surface which chemically binds them. A self-assembled monolayer such as APTMS can be used to bind the quantum dots and remove them from the master patterned stamp, allowing the patterned OTS SAM to be repeatedly filled with quantum dots and stamped. This has been demonstrated using CdTe quantum dots with TGA ligands; however, there are a variety of nano particles with which this technique will work. Therefore by creating a patterned SAM and utilizing selective deposition and appropriate transfer chemistry it is possible to open a new realm of potential device manufacturing.

5:20pm **EM1-MoA11 Solution Processed Quantum Dots for Infrared Imaging**, ***J. Lewis***, *E.J.D. Klem, C. Gregory, G. Cunningham, D. Temple*, RTI International

While InGaAs-based focal plane arrays (FPAs) provide excellent detectivity and low noise for short wave infrared (SWIR) imaging applications, wider scale adoption of systems capable of working in this spectral range are limited by high costs, limited spectral response, and costly integration with Si readout circuits (ROICs). RTI has demonstrated a novel photodiode technology based on a heterojunction between IR-absorbing, solution-processed PbS colloidal quantum dots (CQD) and C_{60} fullerenes that can overcome these limitations of InGaAs FPAs. We have fabricated devices with quantum efficiencies exceeding 50%, and detectivities greater than

10^{12} Jones, that are competitive with the performance of InGaAs photodiodes. Dark currents of ~2 nA/cm^2 were measured at temperatures compatible with solid state cooling. Additionally, by processing these devices entirely at room temperature we find them to be compatible with monolithic integration onto ROICs, thereby removing any limitation on device size. We will show early efforts towards demonstrating a direct integration of this sensor technology onto a Si ROIC IC and describe a path towards fabricating sensors sensitive from the visible to 1700 nm at a cost comparable to that of CMOS based devices. This combination of high performance, dramatic cost reduction, and multispectral sensitivity is ideally suited to expand the use of SWIR imaging in current applications, as well as to address applications which require a multispectral sensitivity not met by existing technologies.

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