NAMBE
Room Tamaya ABC - Session NAMBE2-TuM
III-Nitrides

Moderator: Brelon May, Idaho National Laboratory

10:30am **NAMBE2-TuM-11 Kilo-Volt Class Lateral NiO_x/GaN Super-Heterojunction Diode via Ammonia Molecular Beam Epitaxy (NH_3-MBE)**,
Yizheng Liu, University of California at Santa Barbara*; Zachary Biegler,* University of California Santa Barbara*; Ashley Wissel-Garcia, James Speck, Sriram Krishnamoorthy,* University of California at Santa Barbara

This work reports the fabrication and characterization of the lateral kilo-volt class NiO_x/GaN super-heterojunction (SHJ) diodes via ammonia molecular beam epitaxy (NH_3-MBE), accomplishing ~2.8 kV breakdown voltage, and maximum critical electric field > 1 MV/cm. The Si-doped GaN (~250 nm) was grown at 790 ºC with a 200 sccm NH_3 flow on a semi-insulating Fe-doped GaN-on-sapphire template after an unintentionally doped (UID) buffer layer with two-dimensional sheet charge density (σn~1.1×10^{13} cm^{-2}) and electron mobility (μn~462 cm^2/V•s) confirmed by high-voltage capacitance-voltage (C-V) and room temperature Hall effect measurements.

The MBE grown GaN epilayer underwent a blanket plasma-etch by using BCl_3/Cl_2 reactive ion etching (RIE) to reduce the two-dimensional sheet charge density down to 7.32×10^{12} cm^{-2} to mitigate built-in junction electric field. After optical lithography, the etched GaN was mesa-isolated using RIE, then an e-beam evaporated Ti/Al/Ni/Au (30/120/30/50 nm) metal stack was annealed at 820 ºC in nitrogen (N_2) environment to form high quality Ohmic contact on the mesa, which was confirmed via rectangular transmission line measurements (RTLM). After cathode formation, an 86-nm p^- NiO_x was deposited via reactive magnetron sputtering to form a charge-balanced extension region. The acceptor concentration (N_a) in sputtered p^- NiO_x was extracted to be 8.19×10^{17} cm^{-3} via heterojunction diode capacitance-voltage (C-V) method at 10 kHz, and the N_a concentration was stabilized by a 5-minute N_2 anneal. Following the p^- NiO_x deposition, a ~15-nm p^{++} NiO_x contact layer was sputtered on the sidewall, covering a planar extension portion of the p- NiO_x, then a Ni/Au (50/100 nm) anode Ohmic stack was deposited via e-beam evaporation on p^{++} NiO_x. Finally, a 2-μm epoxy-based polymer photoresist (SU-8) was applied to the SHJ diodes as a passivation layer to conclude device fabrication.

The NiO_x/GaN SHJ diode exhibits a 2-7.5 mA/mm linear forward current density at 5 V, and a reverse leakage of ~10^{-7}-10^{-5} mA/mm under low reverse bias (-5 V) with a rectifying ratio (J_{on}/J_{off}) of 10^5~$10^7$for devices with 16,25,and 50-μm anode-to-cathode distances (L_{AC}). The 50- μm L_{AC} SHJ diodes exhibited the highest breakdown voltage at ~2.8 kV with SU-8 passivation, showing a 5X improvement of breakdown voltage at reverse leakage of 10^{-5} A/mm compared to its reference counterparts that were not charge-balanced. The maximum breakdown field of SHJ diode was extracted to be >1 MV/cm on a 16-μm L_{AC} device.

Acknowledgement: Weacknowledge the funding from U.S. Department of Energy (DOE) ARPA-E OPEN 2021 program (DE-AR0001591).

10:45am **NAMBE2-TuM-12 Limitations and Effects of Heavy Metal Doping in GaN**,
J. Pierce Fix, Montana State University*; Kevin Vallejo,* Idaho National Laboratory*; Nicholas Borys,* Montana State University*; **Brelon May**,* Idaho National Laboratory

The doping of third-party elements is the backbone of the microelectronics industry, as it allows delicate control of electron/hole concentration, but it can also be used to imbue a host matrix with unique magnetic or optical properties. Wurtzite gallium nitride is a widely studied large bandgap semiconductor. There are reports of doping GaN with numerous elements, with some being extensively employed in commercial applications. However, there are still a few elements which remain completely unexplored. This work investigates the doping limits and effects of select transition metals, lanthanoids, and actinoids in GaN. The structural, electronic, and optical properties of these first-of-a-kind combinations are presented. Embedding single crystal wide bandgap materials with additional functionality will provide building blocks for new multifunctional hybrid systems for novel sensors, quantum science, or meta-multiferroics. Leveraging the non-centrosymmetric piezoelectric host matrix and atomic-level control of dopant species could allow for active tuning of proximity and correlated phenomena, potentially opening the door for applications of actinide elements beyond nuclear fuels.

11:00am **NAMBE2-TuM-13 Investigation of Composition Fluctuations and Band Tail States in Plasma Assisted MBE-Grown High Al-Fraction AlGaN**,
***David Storm**, Yuanping Chen, LeighAnn Larkin, Mihee Ji, Gregory Garrett, Anand Sampath, Michael Wraback,* Army Research Laboratory*; Jonathan Pratt, Agnes Xavier, Siddharth Rajan,* Ohio State University

Ultrawide bandgap materials such as AlN and high Al-fraction AlGaN are attractive materials for high power electronic devices. However, while electron mobility in AlGaN grown by MOCVD is well described by transport models incorporating scattering from alloy disorder, dislocations, and phonons, electron mobility in plasma assisted MBE (PAMBE) grown high Al-fraction AlGaN exhibits anomalously low electron mobility, suggesting an additional scattering mechanism is operative. We have grown a series of 500 nm-thick $Al_{0.85}Ga_{0.15}N$ layers at various temperatures between 700 °C and 875 °C by PAMBE. These layers were doped with Si at a nominal concentration of 3×10^{19} cm^{-3}. We observe that both the Hall mobility and carrier density decrease by ~50% as growth temperature increases over the range investigated. In addition, we have observed sub-bandgap emission by photoluminescence spectroscopy and note that the intensity of this sub-bandgap emission increases as the growth temperature of the layers increases. We hypothesize that the density of localized states responsible for the sub-bandgap emission arise from compositional fluctuations in PAMBE-grown AlGaN, and that this density of states increases with growth temperature, leading to more effective filling of the deep localized states by electrons associated with n-type doping, which may open more availability of unoccupied shallow traps in band tail states. The interaction of the doping electrons with these shallow localized states via a “capture and release” mechanism may contribute to the observed reduced electron mobility. We will discuss the effect of growth parameters on compositional fluctuations and optical and transport properties.

11:15am **NAMBE2-TuM-14 Sc-Rich Monocrystalline ScGaN Grown by MBE Exhibits Attractive Ferroelectric Properties**,
***Samuel Yang**, Shubham Mondal, Jae Hun Kim, Zetian Mi,* University of Michigan, Ann Arbor

Solid solutions of wurtzite III-nitrides and rare-earth nitrides form a flourishing class of ferroelectric (FE) nitrides, including ScAlN, ScGaN, YAlN, and quaternary alloys. However, many desirable properties of FE nitrides, including exceptional piezoelectric response, optical non-linearity, and lower coercive fields, only manifest at high Sc compositions. Theoretical studies predict for ScAlN, 56% Sc is possible before transitioning to a nonpolar cubic structure. Nevertheless, growing ScAlN beyond 40% Sc has proven challenging. Alternatively, the solubility of ScN in GaN is predicted to be greater than in AlN. Furthermore, initial studies on ScGaN have recognised the potential for lower coercive fields while maintaining many desirable properties of ScAlN.

To this end, we investigate the MBE growth and FE properties of ScGaN with Sc compositions up to over 50%. 45 nm-thick ScGaN films are grown on GaN-on-sapphire templates under moderately nitrogen rich conditions. EDS confirms Sc compositions of 35%, 47%, and 56% in a series of samples. AFM shows sub-1 nm roughness over 25 μm^2 scan areas, even for $Sc_{0.56}Ga_{0.44}N$. (002) plane XRD rocking curves reveal FWHMs ranging from 650 arcsec to 1550 arcsec for $Sc_{0.35}Ga_{0.65}N$ and $Sc_{0.56}Ga_{0.44}N$, respectively. Furthermore, a (102) plane ϕ scan demonstrates excellent epitaxial registry between $Sc_{0.56}Ga_{0.44}N$ and GaN. Despite large lattice mismatch and distortion, phase-pure single-crystal growth can still be achieved. Electrical characterisation illustrates unambiguous FE switching with decreasing coercive field and remanent polarisation with increasing Sc, matching expectations that greater Sc content flattens the wurtzite structure towards a nonpolar state. Most notably, the coercive field decreases from 2.5 MV cm^{-1} at $Sc_{0.35}Ga_{0.65}N$ to 1.2 MV cm^{-1} at $Sc_{0.56}Ga_{0.44}N$, comparable to members in the HZO family. Moreover, the fatiguing characteristics of $Sc_{0.56}Ga_{0.44}N$ show non-zero polarisation remaining after 10^9 cycles, significant improvement over 10^6-10^7 cycles in MBE-grown $Sc_{0.2}Al_{0.8}N$. These results serve as a first glance into the realm of Sc-rich FE nitrides to harness outstanding FE, piezoelectric, and optical properties in a nitride platform. Further study is anticipated to continue developing the advanced epitaxy to grow ScGaN towards the predicted phase transition content of 66% Sc and beyond.

11:30am **NAMBE2-TuM-15 Towards High Wall-Plug Efficiency Nanowire-based Red Micro-LEDs**,
***Yifu Guo**, Ayush Pandey, Reddeppa Maddaka, Yixin Xiao, Yakshita Malhotra, Jiangnan Liu, Yuanpeng Wu, Kai Sun, Zetian Mi,* University of Michigan, Ann Arbor

Displays for future technologies such as augmented and virtual reality require ultra-high resolution and efficient power consumption, for which III-nitride LEDs at the (sub)micron scale (micro-LEDs) have been under intense investigation. Conventional top-down processing of micro-LEDs, however, requires a plasma etch to define mesas for individual devices on a wafer. As the mesa size shrink down to the micrometer regime, device efficiency loss due to plasma-induced non-radiative centers on the sidewall surfaces is further exacerbated with increasing surface-to-volume ratio. In addition, while the III-nitride family has shown immense promise for micro-LED applications due to a host of desirable properties (such as tunable bandgap across the entire visible spectrum and low surface recombination velocity), it also presents a host of material challenges, such as the large lattice mismatch and lack of intermiscibility between InN and GaN and spectral variation under different operating conditions due to quantum-confined Stark effect, that must be overcome for the device's eventual commercialization.

Here, we show that by utilizing a combination of strategies for relieving strain and enhancing the carrier injection efficiencies, including the bottom-up approach, nitrogen polarity, Mg-doped AlGaN electron-blocking layer, and a p-GaN layer with gradient doping, unprecedentedly high wall-plug efficiency for a sub-micron red LED has been achieved. The bottom-up approach, achieved via selective area epitaxy, eliminates the need for a plasma etch step through the device stack during device fabrication, thereby protecting the active region from the deleterious surface damage mentioned above. In addition, the bottom-up nanowires form a strain-relaxed and nearly defect-free template that allows for high quality InGaN active region with the very high levels of indium incorporation needed for red emission. To reduce electron overflow and achieve high wall-plug efficiency with these N-polar red-emitting nanowires, we have also incorporated an AlGaN EBL, as well as a p-GaN layer with graded Mg-doping.

The resultant nanowire-based InGaN micro-LED exhibited an emission wavelength of ~650 nm at a peak external quantum efficiency of ~12.8% and a wall-plug efficiency of ~12.2%, corresponding to a peak electrical efficiency of ~95%. Through this work, we demonstrate that the hitherto low electrical efficiency of nanowire-based devices can be overcome through careful design of the device heterostructure and that such devices can form the foundation of future micro-LED displays.

11:45am **NAMBE2-TuM-16 High Permittivity Epitaxial $BaTiO_3$ Thin Films on AlGaN/GaN Heterostructures for RF Electronics***, **Eric Jin**, Vikrant Gokhale, James Champlain,* US Naval Research Laboratory*; James Hart,* NOVA Research, Inc.*; Andrew Lang, Matthew Hardy, Neeraj Nepal, D. Scott Katzer, Brian Downey, Virginia Wheeler,* US Naval Research Laboratory

Development of AlGaN/GaN high electron mobility transistors (HEMTs) has resulted in a myriad of applications, including high output RF power amplifiers, owing to the high breakdown field strength and excellent transport characteristics observed in III-nitride semiconductors. However, despite their wide bandgap, breakdown voltage in lateral HEMTs is ultimately limited due to the high peak electric fields leading to premature breakdown when compared to theoretical limits. Field management strategies leveraging high permittivity gate dielectrics including $BaTiO_3$ (BTO) have recently been shown to improve electric field distribution, thereby increasing breakdown voltage. These heterostructures typically utilize BTO dielectric layers deposited by RF sputtering, which are susceptible to low crystal quality or polycrystalline films, having lower dielectric constants (κ) than bulk or single crystalline BTO. Enhancing the crystal quality of the BTO film can both improve the quality of the oxide/nitride interface and increase κ, leading to further improvements in device voltage handling.

In this work, we demonstrate the growth of epitaxial (111)-oriented BTO thin films onto AlGaN/GaN HEMT heterostructures by RF-plasma assisted oxide molecular beam epitaxy. An epitaxial 2 nm $SrTiO_3$ (STO) / 1 nm TiO_2 bilayer stack is first deposited on the AlGaN surface to reduce the lattice mismatch and to provide a seed layer to facilitate crystalline and well-oriented BTO growth. The addition of the STO layer is necessary to achieve highly crystalline BTO due to its tetragonal structure and slightly larger unit cell volume compared to STO. Transmission electron microscopy imaging confirms the epitaxial orientation of the BTO film. Van der Pauw Hall effect measurements show no significant change in the sheet resistance, electron mobility, or electron density of the GaN channel due to the presence of the epitaxial BTO layers.

We investigate the effect of BTO growth temperature on structural and electrical properties by depositing the BTO layers at substrate temperatures ranging from 550-850 °C and find that the BTO crystallinity improves as growth temperature is increased. *I-V* and *C-V* measurements on test capacitor structures fabricated on the BTO on AlGaN/GaN heterostructures demonstrate trends of increasing κ values of the oxide layers and reduced leakage with increasing BTO growth temperature. A BTO κ of 340 is measured on a sample grown at 850 °C. Finally, loss tangent measurements indicate tan δ values as low as ~2×10^{-3}. These results indicate a promising approach to building high quality HEMTs with improved interfaces and enhanced RF and power performance.

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