MBE
Room Max Bell Auditorium - Session MBE-MoM
Novel III-N Growth and Applications/III-Nitrides for Electronics

Moderators: Thomas Tiedje, University of Victoria, Isaac Hernandez-Calderon, CINVESTAV, Maria Tamargo, City College of New York, City University of New York

8:30am **MBE-MoM-1 MBE Innovator Award Talk: Evolution, Development and Commercialization of the Quantum Dot Laser: Brief History and Recent Progress**, ***Pallab Bhattacharya***, University of Michigan **INVITED**

The advantages of using quantum dots in the active (gain) region of semiconductor lasers were obvious. However, a technique to incorporate these nanostructures in the laser heterostructure was not available. The breakthrough occurred with the invention of selfassembled quantum dots during the growth of strained (mismatched) InGaAs/GaAs heterostructures. This was followed by quantitative characterization of the epitaxial process and optimization of the optical and structural properties of the quantum dots. It was evident that multiple quantum dot layers could be inserted *in-situ* in laser heterostructures. Subsequently 980nm, 1.3µm and 1.55µm lasers with unprecedented characteristics such as $T_o \rightarrow \infty$, low chirp, small α-factor and high differential gain were developed and also quantum dot lasers on silicon substrates. More recently, the author's group demonstrated the first III-nitride visible quantum dot lasers, with the emission wavelength extending to 630nm (red). Use of quantum dots provides more advantages in the III-nitride system than the conventional III-V system. The ability to epitaxially grow blue-, green- and red- emitting quantum dots enables the realization of all-semiconductor white LEDs. Finally, the characteristics of 1.3µm III-nitride dot-in-nanowire optical interconnects on (001)Si substrate, consisting of a diode laser, waveguide and photodetector, will be briefly described. Quantum dot light sources are now used in a number of applications and these will be highlighted.

9:15am **MBE-MoM-4 High Growth Rate Plasma Considerations for Indium-rich III-nitrides**, ***Evan Clinton***, *E Vadiee, W Doolittle,* Georgia Institute of Technology

A high nitrogen flow rate Veeco plasma source has been employed to achieve GaN growth rates above 10 µm/hr utilizing the metal modulated epitaxy (MME) growth technique in a plasma-assisted molecular beam epitaxy (PAMBE) reactor. High growth rates enable thick buffer layers which can lower threading dislocation densities, essential for III-nitride optoelectronic devices such as solar cells and green light emitting diodes (LEDs). Additionally, PAMBE is capable of growing single phase $In_xGa_{1-x}N$ films for all indium compositions ($0 \leq x \leq 1$). It is shown that as the indium content increases and the bandgap of the material decreases, the surface becomes more sensitive to plasma-induced damage, as observed via atomic force microscopy (AFM) and reflection high energy electron diffraction (RHEED). Thus, in order to grow thick $In_xGa_{1-x}N$ films with fast growth rates, the plasma induced crystal damage must be minimized by optimizing the nitrogen plasma discharge. *In-situ* plasma discharge monitoring and optimization can be accomplished with a combination of optical emission spectroscopy (OES) as well as utilizing a flux gauge collector pin as a Langmuir probe. OES determines a plasma's molecular and atomic content, while the Langmuir probe current-voltage characteristics can determine the plasma discharge floating acceleration voltage and ion densities. In this work, correlations between plasma conditions and crystal quality are established. It is shown that by increasing the nitrogen flow the positive ion content increases, however, the acceleration voltage reduces. Additionally, a higher applied plasma power results in a negligible increase in positive ion content. In particular, AFM results demonstrate that the surface pit density of MME grown InN films dramatically reduces with reduced ion content. Finally, a roadmap will be presented to minimize damage in high indium content III-nitride devices.

9:30am **MBE-MoM-5 Molecular Beam Epitaxy of III-Nitride Nanowires on Amorphous and Nanocrystalline Metals**, ***Brelon May***, *E Hettiaratchy, R Myers,* The Ohio State University

The high surface area to volume ratio of nanowires allows them to have a larger degree of strain relaxation relative to their thin film counterparts. This enables high quality material to be grown on a variety of materials, including polycrystalline metal foils [1]. However, inhomogeneity associated with self-assembled growth reduces device efficiency. The polycrystalline nature of typical metal foils adds additional nonuniformities related to the metallic microstructure, e.g. grain boundaries and orientations (Fig. 1(a)). One possible solution is to tailor the substrate microstructure to have grain sizes of the same order as the nanowires, such that flux shadowing would limit the impact of microstructure variation. A more ideal option is to eliminate the microstructure altogether through the use of a metallic glass substrate i.e. amorphous metal. Here we demonstrate the growth of III-Nitride nanowires on Pt thin films as well as on amorphous metal foils. SEM measurements show that growth on amorphous foils enhances not only the uniformity of the density but also results in a higher degree of vertical nanowire alignment (Fig. 1(b)). The variations in optical and structural properties of the nanowire ensembles will be discussed in relation to the substrate microstructure.

9:45am **MBE-MoM-6 RF-Plasma MBE Growth of Epitaxial Metallic TaN_x Transition Metal Nitride Films on SiC**, ***D. Scott Katzer***, *N Nepal, M Hardy, B Downey, D Storm, D Meyer,* U.S. Naval Research Laboratory

Integration of epitaxial metal layers within semiconductor devices will enable substantial performance benefits, design flexibility, and novel device structures such as metal-base transistors [1] and integrated epitaxial superconductor / semiconductor heterostructures [2]. We have previously reported on the use of RF-plasma MBE to epitaxially grow metallic niobium nitride (NbN_x) thin films and III-N/NbN_x heterostructures on hexagonal SiC substrates [3-5]. More recently, we have reported on novel device lift-off processing enabled by the selective etching of NbN_x under III-N HEMTs [6]. In this presentation, we will discuss our recent work on the epitaxy of a similar transition metal nitride (TMN) material: TaN_x . As with NbN_x , the equilibrium phase diagram for TaN_x is complex, so demonstrating control of the TaN_x phase is important for practical applications. We have successfully grown single-phase thin films of single-crystal TaN_x on 3"-diameter SiC substrates using a customized Scienta-Omicron PRO-75 MBE system equipped with a six-pocket electron-beam evaporator to generate the Ta flux. We will discuss the MBE growth conditions for TaN_x and demonstrate the epitaxy of AlN/TaN_x heterostructures on SiC. The films were characterized in-situ using RHEED, and ex-situ using optical and atomic-force microscopy, contactless sheet resistance, x-ray diffraction, and transmission electron diffraction.

This work was funded by the Office of Naval Research.

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+ Author for correspondence: scott.katzer@nrl.navy.mil

10:30am **MBE-MoM-9 Magneto-Photoluminescence Properties of an AlGaN/GaN 2DEG Grown on Bulk GaN**, ***Stefan Schmult,*** TU Dresden, Germany; *V Solovyev,* Institute of Solid State Physics RAS, Russia; *S Wirth,* Max-Planck-Institute for Chemical Physics of Solids, Germany; *A Grosser,* NaMLab gGmbH, Germany; *T Mikolajick,* TU Dresden & NaMLab gGmbH, Germany; *I Kukushkin,* Institute of Solid State Physics RAS, Russia

Landau level (LL) splitting of the density of states at moderate magnetic fields (~1T) is characteristic for high-quality 2-dimensional electron gases (2DEGs) confined in semiconductor heterostructures. In magneto-transport measurements this LL splitting leads to pronounced Shubnikov-de Haas oscillations in the longitudinal resistance and emergence of the quantum Hall effect. Reports on the optical detection of LLs in magneto-photoluminescence (PL) spectra are so far speculative for 2DEGs formed in AlGaN/GaN heterostructures.

Here, the LL splitting in a 2DEG confined at an $Al_{0.06}Ga_{0.94}N$/GaN interface is spectroscopically confirmed. The ultra-pure GaN/AlGaN/GaN (1µm/16nm/3nm) layer stack was grown by MBE on 650µm thick semi-insulating GaN with a vendor-specified density of threading dislocations (n_{TDD}) < 1e6cm^{-2}. Atomic force microscopy reveals 5x5µm^2 surface sections without a single defect, verifying the defect level to < 4e6cm^{-2}. An active area is laterally defined in Hall bar geometry, allowing for simultaneous measurements of magneto-transport and –PL under steady illumination at low-temperatures and magnetic fields up to 15 Tesla. The B-field induced oscillations commence in both cases at ~2T. Identical frequencies governing both oscillation types confirm the inherent 2D nature of the discussed PL features. The energy splitting between the PL LLs allows for extraction of an effective electron mass of ~0.24 m_e. Optical detection of the 2DEG represents a contactless method - even on wafer level - independent of e.g. lateral device definition, electrical contact issues or parasitic conduction paths.

10:45am **MBE-MoM-10 Kinetically Limited Growth of High Scandium Fraction Scandium Aluminum Nitride***, **Matthew Hardy**, B Downey, N Nepal, D Storm, D Katzer, D Meyer,* U.S. Naval Research Laboratory

Thin film AlN-based resonators are the industry standard for microwave-frequency filters used in 4G cell phone technology, and a variety of other RF applications [1]. $Sc_xAl_{1-x}N$ has the potential to replace AlN in next generation devices due a factor of five improvement in piezoelectric response for x = 0.43 [2]. ScAlN is previously been grown by reactive sputtering, which often has relatively high impurity incorporation and high densities of structural defects. Growth of electronic-device-quality ScAlN by molecular beam epitaxy (MBE) has been demonstrated in high-electron-mobility transistor (HEMT) structures using lattice-matched $Sc_{0.18}Al_{0.82}N$barriers [3]. MBE-growth of high ScN mole fraction ScAlN will enable novel acoustoelectric devices, such as resonant body HEMTs, which take advantage of both the piezoelectric and electronic properties of ScAlN.

200-nm $Sc_xAl_{1-x}N$ samples were grown on 10-nm AlN nucleation layers on 4H-SiC substrates using an RF-plasma MBE equipped with a high temperature effusion cell to supply Sc flux and a dual-filament effusion cell to supply Al flux. Samples with ScN molar fraction varying between 0.10–0.38 were grown at substrate thermocouple temperatures ranging from 400 °C to 920 °C. At moderate ScN fractions of 0.10–0.25, the substrate temperature had minimal impact on ScAlN quality, with films grown at lower temperature having rougher surfaces, but all samples were single-phase wurtzite ScAlN. Reflection high-energy electron diffraction (RHEED) patterns of samples with x = 0.38 grown at 800 °C and 400 °C are shown in Fig. 1, and cross-sectional transmission electron micrographs (TEM) of the same two samples are shown in Fig. 2. The RHEED pattern for the 800 °C-grown sample in Fig. 1(a) shows an extra set of first order spots, consistent with rotated cubic domains, while the TEM image in Fig. 2(a) shows evidence of rock-salt cubic inclusions. However, when grown at 400 °C, both RHEED in Fig. 1(b) and TEM in Fig. 2(b) show single-phase wurtzite ScAlN.

This work was funded by the Office of Naval Research.

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11:00am **MBE-MoM-11 Low Resistivity Al-rich AlGaN Grown by Plasma-assisted Molecular Beam Epitaxy***, **Ayush Pandey**,* University of Michigan*; X Liu,* McGill University, Canada*; D Laleyan, K Mashooq, E Reid, W Shin, P Bhattacharya, Z Mi,* University of Michigan

A highly conductive p-type AlGaN layer is crucial for obtaining high efficiency deep ultraviolet (UV) light emitting diodes (LEDs) and semiconductor laser diodes. Mg, which is a common p-type dopant for III-nitrides has a very large activation energy (up to 500-600 meV) in Al-rich AlGaN [1-3], and its solubility decreases significantly with increasing Al composition [4, 5]. Resistivity values ~10^2 to 10^4 Ω·cm have been commonly reported for p-type AlGaN epilayers with Al compositions ~80%, compared to <1 Ω·cm for p-type GaN.

We report on the achievement of low resistivity (~1-10 Ω·cm) p-type AlGaN epilayers with Al compositions in the range of 75-95% by using plasma-assisted molecular beam epitaxy. The growth was carried out under slightly metal rich conditions to ensure a smooth surface and good crystalline quality. Detailed characterization of the samples was carried out using X-ray diffraction (XRD), atomic force microscopy, and Hall effect measurements. We measured a hole concentration of ~1×10^{18} cm^{-3} and mobility ~6 cm^2/V·sec for AlGaN with Al composition ~75% at room temperature, which are significantly higher than previously reported values for AlGaN grown by MOCVD. Moreover, a relatively high hole concentration ~4×10^{17} cm^{-3} was achieved for AlGaN with Al composition >90%. The resistivity varies from ~1 to 4 Ω·cm with increasing Al composition from 75% to 92%. Detailed temperature dependent Hall measurements showed a small activation energy (~15 meV) for hole concentration near room temperature, suggesting the important role of hole hopping conduction in the Mg impurity band. The realization of high efficiency AlGaN deep UV LEDs is in progress and will be reported.

11:15am **MBE-MoM-12 RF-MBE Growth of AlN/GaN/AlN Resonant Tunneling Diodes on Freestanding GaN and GaN Templates***, **David Storm**,* U.S. Naval Research Laboratory*; T Growden,* The Ohio State University*; W Zhang,* Wright State University*; S Katzer, M Hardy, D Meyer,* U.S. Naval Research Laboratory*; E Brown,* Wright State University*; P Berger,* The Ohio State University

AlN/GaN/AlN resonant tunneling diodes (RTD) grown by RF plasma-assisted MBE on low dislocation-density, freestanding (FS) GaN substrates exhibit repeatable, stable, and hysteresis-free negative differential resistance at room temperature [1], extremely high current density [2], and near-UV cross-gap light emission [3]. In order to investigate the effects of growth conditions and dislocation density on the materials and electronic properties, we have grown AlN/GaN/AlN RTD structures by RF-MBE on hydride vapor-phase epitaxy (HVPE) grown FS GaN substrates and on metal organic chemical-vapor deposition (MOCVD)-grown GaN templates on sapphire. Nominally identical sets of structures were grown in the Ga-rich and Ga-stable growth regimes on each substrate type. The as-grown samples were characterized by optical microscopy, atomic force microscopy (AFM), and high-resolution x-ray diffractometry (HRXRD). Ga droplets were observed on the as-grown surfaces of the samples grown below 800 °C, and no droplets were observed on samples grown at or above 800 °C. AFM reveals surface morphologies of samples grown Ga-rich to be smoother, as expected; however, previous investigations indicate that smoother surface morphology does not correlate with improved device properties [4]. Dynamical simulations of the HRXRD data suggest trends toward thinner AlN barriers and thicker GaN wells in samples grown on freestanding GaN, potentially indicative of greater interfacial roughness, as growth temperature increases and the growth mode transitions from Ga-rich to Ga-stable. RTDs have been fabricated on all samples and devices tested. Electronic device results will be presented.

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+ Author for correspondence: david.storm@nrl.navy.mil

11:30am **MBE-MoM-13 Low-resistance GaN Homojunction Tunnel Diodes and Low Voltage Drop Tunnel Contacts***, E Vadiee, **Evan Clinton**, W Doolittle,* Georgia Institute of Technology

The III-nitride material system is promising for optoelectronic and electronic applications. There have been continuing efforts in the development of GaN-based tunnel junctions (TJs) as one of the main remaining challenges in III-nitride materials, which can enable the next generation of III-nitride devices. The TJ can significantly improve the efficiency of visible and ultraviolet emitters as well as solar cells. However, achieving GaN-based TJs are extremely challenging due to the large band gap and the low hole concentration typical in GaN.

In this work, for the first time, we present a high-conductance GaN homojunction tunnel diode with a distinctive negative differential resistance (NDR) at a forward bias of 1.35 V and an intrinsic reverse Zener characteristic grown via metal modulated epitaxy (MME). The most recent achievements in the growth of extremely high doped GaN materials are also presented. In addition, the effect of the Mg doping concentration on the carrier transport of the TJs is studied, showing an increase in the forward and reverse tunneling current densities, the peak-to-valley ratio (PVR), and the NDR peak voltage by increasing the Mg doping concentration. In particular, the TJ using Mg and Si doping concentrations of 5×1020 and 7×1020 cm^{-3} shows a current density of 400 A/cm^2 at -1.2 V and PVR of ~1.1.

Furthermore, the temperature dependent current-voltage (I-V) characteristics of the TJ are discussed to provide insight into the nature of the tunneling behavior in the wide bandgap GaN. We present defect-assisted tunneling as the main carrier transport mechanism rather than interband tunneling. The low-temperature I-V characteristics of the best-performing TJ revealed repeatable NDR features with no hysteresis and PVR of ~1.3, which indicates a minimal carrier freeze-out in the GaN: Mg (see Fig 1). The highest silicon-doped n++/p++/i/n tunnel-contacted diode demonstrates a turn-on voltage of 3.12 V, only 0.14 V higher than that of the p/i/n control diode, and an improved specific on-resistance of 3.24 x10^{-4} Ωcm^2, which is 13% lower than that of the control diode.

Finally, recent results on low-resistance TJ contacts to LEDs with minimal voltage drop and the first demonstration of InGaN solar cells with p-n GaN homojunction tunnel contacts with an open-circuit voltage of ~2.2 V are presented.

11:45am **MBE-MoM-14 On the Efficiency and Long-term Stability of MBE-grown III-Nitride Nanostructures for Unassisted Overall Water Splitting***,*
Faqrul A. Chowdhury*, H Tran, H Guo,* McGill University, Canada*; Z Mi,* University of Michigan

The direct conversion of sunlight to hydrogen via water splitting has emerged as one of the key technologies to achieve energy sustainability. Progress in this field, however, has been limited by the low photocatalytic efficiency of conventional metal-oxide materials. We have recently demonstrated that nearly defect-free GaN-based nanostructures can meet the thermodynamics for overall water splitting (OWS) [1]; and by tuning the surface Fermi-level through controlled Mg-dopant incorporation, the apparent quantum efficiency for solar-to-hydrogen conversion can be enhanced by nearly two orders of magnitude under UV [2] and visible light illumination [3-4]. In this work, we demonstrate multi-band InGaN nanosheet photochemical diode (PCD) structures, which can spontaneously induce charge carrier separation and steer charge carriers toward the distinct redox sites for water oxidation and proton reduction. During the synthesis of InGaN photochemical diode nanosheet structure, p-type dopant (Mg) concentrations are rationally tailored, which induces a large built-in electric field between the two parallel surfaces. Due to the presence of a net built-in potential ~300 meV (Δ*E*) along the lateral dimension, the two surfaces are enriched with photo-generated holes and electrons to perform water oxidation and proton reduction reactions, respectively [5]. With spatially separated catalytic sites and reduced carrier recombination, the nanoscale PCDs exhibit stoichiometric H_2 and O_2 evolution, with a production rate of ~1.62 mmol $h^{-1}cm^{-2}$ and ~0.784 mmol $h^{-1}cm^{-2}$, respectively, which is equivalent to a solar-to-hydrogen efficiency over ~3%. We are currently developing novel III-Nitride nanostructured device on Si, which can demonstrate unprecedented performance-stability for more than ~580 hours in unassisted photochemical water splitting reaction when the surface is modified with suitable co-catalyst nanoparticles. With structural engineering, we aim to further enhance the solar-to-hydrogen efficiency in the range of 5-10%.

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