Electronic Materials and Photonics Division
Room: 14 - Session EM+NS-ThA

Wide and Ultra-wide Band Gap Materials for Electronic Devices: Growth, Modeling, and Properties
Moderators: Michael Filler, Georgia Institute of Technology, Rachael Myers-Ward, U.S. Naval Research Laboratory

2:20pm **EM+NS-ThA1 Synthesis of β-Ga2O3 Thin Films on SiC by Molecular Beam Epitaxy**, ***Neeraj Nepal**, D.S. Katzer, D.F. Storm, M.T. Hardy, B.P. Downey, D.J. Meyer*, U.S. Naval Research Laboratory

Recently, there has been great interest in β-Ga2O3 as a next generation ultra-wide bandgap semiconductor (UWBGS) for high-power/temperature electronics devices. However, it has low thermal conductivity of β-Ga2O3 may limit device performance. One strategy to improve performance of Ga2O3 based devices is through heterostructure design on high thermal conductivity substrate. In this paper, we report growth and characterization of 100 nm thick β-Ga2O3 on SiC by molecular beam epitaxy (MBE) at 650 °C. First, the growth parameter space such thermocouple measured growth temperature, relative Ga flux, and oxygen plasma were varied to grow β-Ga2O3 films on c-plane sapphire substrates. For an O2 plasma flow of 1 sccm (2.5x10-5 torr) X-ray diffraction shows weak facets of β-Ga2O3 appear regardless of the Ga flux and temperature, however for <0.6 sccm O2 flow, smooth β-Ga2O3 [(-201)||(0001)] grows on c-plane sapphire. Optimized MBE growth conditions on sapphire substrate were used to grow β-Ga2O3 on SiC. Single phase MBE β-Ga2O3 film on SiC grown at 650 °C are insulating, have rocking curve full-width-at-half-maximum of 720 arc-sec with root mean square surface roughness of less than 2 nm. In this paper we will discuss MBE growth parameter space of β-Ga2O3 on sapphire and the structural, morphological, and electrical properties of MBE grown β-Ga2O3 thin films on SiC.

2:40pm **EM+NS-ThA2 Growth and Characterization of *α*-, *β*-, and *ε*-Ga_2O_3 Epitaxial Layers**, ***Lisa Porter**, Y. Yao, L.A.M. Lyle,* Carnegie Mellon University*, S. Okur, G.S. Tompa, T. Salagaj, N. Sbrockey*, Structured Materials Industries, Inc.

Increasing global demand for energy makes urgent the need for highly efficient high-power electronics for energy conversion and transport. Although silicon devices have been traditionally used for high-power electronics, wide bandgap semiconductors (e.g., SiC and GaN) are much more efficient for these applications, because they can withstand higher electric fields with less material and reduced energy loss. However, the substrates of both materials are still very expensive. A very promising alternative to SiC and GaN is gallium oxide, Ga_2O_3, which has an even larger bandgap than the former two materials. The availability of this material presents new possibilities for disruptive devices and technologies that could translate to even greater energy efficiencies at lower cost than predicted for SiC and GaN. Polished 2-in diameter, single-crystal wafers of the monoclinic *β*-phase can be grown using melt-growth methods and are commercially available. However, there is increasing interest in the other Ga_2O_3 phases, particularly the metastable corundum-structured *α*- and hexagonal-structured *ε*-Ga_2O_3 phases because of their higher symmetry and simpler epitaxial relations to c-plane sapphire, in addition to the possibility of producing functional heterostructures or tunable bandgaps through alloying. We have successfully grown epitaxial films of *α*-, *β*- and *ε*-phases on c-plane sapphire using different precursors and growth conditions. The *α*- and *ε*-phases have generally been reported in the literature to form at lower growth temperatures than the *β*-phase. However, we observed a change in phase formation at the same growth temperature by changing our growth technique and Ga precursor from metalorganic chemical vapor deposition (MOCVD) and trimethlygallium to halide vapor phase epitaxy (HVPE) and gallium chloride. Data from x-ray diffraction, scanning electron microscopy and high-resolution transmission electron microscopy will be presented to illustrate the different epitaxial films and orientation relationships. The results of secondary ion mass spectrometry depth profiles, which showed compositional differences within the different phases, will also be presented. The authors wish to acknowledge the Office of Naval Research under contract no. N00014-16-P2059.

3:00pm **EM+NS-ThA3 Ultra-wide-bandgap Ga_2O_3 Material and Electronic Device Technologies**, ***Masataka Higashiwaki**, M.H. Wong,* National Institute of Information and Communications Technology, Japan*, K. Konishi,* Tokyo University of Agriculture and Technology, Japan*, Y. Nakata, T. Kamimura,* National Institute of Information and Communications Technology, Japan*, K. Sasaki, K. Goto,* Tamura Corporation, Japan*, A. Takeyama, T. Makino, T. Ohshima,* National Institutes for Quantum and Radiological Science and Technology, Japan*, H. Murakami, Y. Kumagai,* Tokyo University of Agriculture and Technology, Japan*, A. Kuramata, S. Yamakoshi*, Tamura Corporation, Japan **INVITED**

Recently, gallium oxide (Ga_2O_3) has attracted much attention as a candidate for future power and harsh environment electronics due to its extremely large bandgap of 4.5 eV and the availability of economical melt-grown native substrates. In this talk, following a short introduction of the material properties of Ga_2O_3, we will discuss our recent progress in the development of Ga_2O_3 metal-oxide-semiconductor field-effect transistors (MOSFETs) and Schottky barrier diodes (SBDs), including Ga_2O_3 thin-film epitaxial growth technologies by molecular beam epitaxy (MBE) and halide vapor phase epitaxy (HVPE).

State-of-the-art Ga_2O_3 MOSFETs with a gate-connected field plate (FP) were fabricated using MBE-grown Ga_2O_3 homoepitaxial layers. The devices showed excellent room-temperature (RT) characteristics such as a record high off-state breakdown voltage (V_{br}) of 755 V, a large drain current on/off ratio of over nine orders of magnitude, and DC-RF dispersion-free output characteristics [1]. Furthermore, the MOSFETs demonstrated strong prospects of Ga_2O_3 devices for extreme environment electronics by virtue of their stable high-temperature operation up to 300°C and strong radiation hardness against gamma-ray irradiation [2].

We have also fabricated and characterized Ga_2O_3 FP-SBDs on n^--Ga_2O_3 drift layers grown by HVPE [3-5]. The illustrative device with a net donor concentration of 1.8×10^{16} cm^{-3} exhibited a specific on-resistance of 5.1 $m\Omega\cdot cm^2$ and an ideality factor of 1.05 at RT. Successful FP engineering resulted in a high V_{br} of 1076 V. Note that this was the first demonstration of V_{br} of over 1 kV in any Ga_2O_3 power device. The maximum electric field in the Ga_2O_3 drift layer at the condition of destructive breakdown was estimated to be 5.1 MV/cm by device simulation, which is about two times larger than the theoretical limits for SiC and GaN.

This work was partially supported by Council for Science, Technology and Innovation (CSTI), Cross-ministerial Strategic Innovation Promotion Program (SIP), "Next-generation power electronics" (funding agency: NEDO).

[1] M. H. Wong *et al.*, IEEE Electron Device Lett. **37**, 212 (2016), [2] M. H. Wong *et al.*, Proc. 75th Device Research Conference II-B.4, 2017, [3] K. Konishi *et al.*, Appl. Phys. Lett. **110**, 103506 (2017), [4] K. Nomura *et al.*, J. Cryst. Growth **405**, 19 (2014), [5] H. Murakami *et al*., Appl. Phys. Express **8**, 015503 (2015).

4:00pm **EM+NS-ThA6 Reactive Magnetron Sputtering of Titanium Nitride and Titanium Aluminum Nitride on Lithium Niobate for Electronic and Opto-Electronic Applications**, ***Amber Reed**, H.A. Smith, D.C. Abeysinghe, P.J. Shah, L. Grazulis, M.J. Hill, M.E. McConney, B.M. Howe, A.M. Urbas*, Air Force Research Laboratory

High temperature stability, hardness, abrasion resistance, chemical stability and potential complimentary metal-oxide semiconductor process compatibility, combined with a high electrical conductivity make titanium nitride (TiN) an important material for electronic and opto-electronic applications. TiN is particularly important as an electrode material due to its oxidation resistance, which can be improved by alloying it with aluminum nitride to form titanium aluminum nitride ($Ti_{1-x}Al_xN$). In addition to its use as an electrode, TiN is also a promising plasmonic material because, similar gold, it possesses a zero crossover wavelength in the visible region. The ability to synthesize high quality TiN crystals on different electronic substrates would greatly facilitate its incorporation in electronic and opto-electronic devices. One particular material of interest is lithium niobate ($LiNbO_3$), which possesses unique piezoelectric, opto-electronic and nonlinear optical properties. Synthesis of high quality TiN on $LiNbO_3$ would allow for integration of TiN into acoustic devices (i.e. SAWs and BAWs), optical modulators, and other electronic and opto-electronic devices.

In this work, we demonstrate the synthesis of high quality epitaxial TiN crystals on Z-cut $LiNbO_3$ substrates. We also discuss the growth of TiN and $Ti_{1-x}Al_xN$ on Y-cut $LiNbO_3$. While the (001) plane of Z-cut $LiNbO_3$ creates a template for epitaxial growth of (111)-oriented TiN crystals, similar to growth on (001)-oriented sapphire, the (010) plane of Y-cut $LiNbO_3$ is equally lattice matched to the TiN (001) and (101) planes which results in competitive growth of those two orientations. Alloying the TiN with AlN

exacerbates this issue as the lattice constant shrinks with increased AlN content. We investigate the role of deposition power, nitrogen gas fraction, and substrate temperature and ion flux impingement on the competitive growth to determine the optimal growth conditions to promote epitaxy. Films are characterized using x-ray diffraction (XRD), atomic force microscopy (AFM), transmission electron microscopy, ellipsometry and electrical measurements. XRD and AFM of TiN on Z-cut $LiNbO_3$ show remarkably smooth (< 220 pm RMS roughness) epitaxial films. Ellipsometry measurements of the TiN on Z-cut $LiNbO_3$ reveal carrier concentrations up to 4.0 $x10^{22}$ cm^{-3}, mobilities of ~3.2 $cm^2/(V\ s)$ and a $\varepsilon_1/\ \varepsilon_2$ of 1.00 to 3.34 at a wavelength of 1550 nm.

4:20pm **EM+NS-ThA7 Growth and Property Analysis of Doped GaN-GaAlN Heterostructures on Low- and High-temperature AlN/Sapphire Templates**, ***Nikolaus Dietz***, *B.G. Cross, M. Vernon,* Georgia State University*, R. Collazo, R. Kirste, S. Mita, Z. Sitar*, North Carolina State University

The developing of radiation-hard UV solid state avalanche photodiodes (APD's) based on group III-Nitride wide band gap materials have a wide application area from solar blind detector to wavelength specific PMT based detector devices that can be tuned in the 220 nm to 450 nm wavelength range, tailored to specific scintillators of interest. This contribution focuses on closely lattice-matched, high-quality GaN a substrate technologies using metalorganic chemical vapor deposition (MOCVD) technique, which provide sufficient high-quality AlGaN layers and heterostructures with high phase uniformity and low dislocation density for low leakage currents, to enable avalanche mechanisms, low leakage currents, high performance characteristics and reliability of the devices.

We will present results on the growth and doping of GaN/GaAlN heterostructures deposited on low- and high-temperature AlN/Sapphire template structures, using a customized D125 Veeco MOCVD reactor system. The structural quality of the initial GaN layer grown on various AlN-/GaN-sapphire template structure has been analyzed and is accessed regarding its resulting dislocation and defect densities, using XRD, Raman and FTIR spectroscopy. The influence of Silicon n-doping in GaN and $Ga_{0.9}Al_{0.1}N$ epilayers on the defect density was analyzed XRD and the dopant incorporation by SIMS analysis.

4:40pm **EM+NS-ThA8 A Thermodynamic Supersaturation model for the Growth of AlGaN by MOCVD**, ***Ramón Collazo***, *S. Washiyama, I. Bryan,* North Carolina State University*, P. Reddy, S. Mita,* Adroit Materials Inc.*, Z. Sitar*, North Carolina State University **INVITED**

AlGaN have been considered to be essential for the development of optoelectronic and electronic devices such as deep UV LEDs and other power devices. However, even under well-controlled growth conditions it is difficult to precisely predict the behavior of AlGaN growth with regards to Al-concentration and related defect incorporation. We have developed a thermodynamic model for the calculation of the Ga supersaturation during the growth of GaN by metalorganic chemical vapor deposition (MOCVD), which was successfully used to predict incorporation of impurities such as carbon as well as the surface morphology (Mita et al., JAP 104, 13521). This model was extended to evaluate the supersaturation of Al and Ga in AlGaN growth and to allow for the prediction of the properties of MOCVD grown AlGaN layers. Non-linear equations for Al and Ga equilibrium vapor pressure calculation describe the process under the following assumptions: (1) under low total pressure, gas phase reactions between the metalorganics and NH_3 are negligible; the III metal precursors are irreversibly cracked on the growth surface, thus, Al, Ga, NH_3, H_2 and N_2 are analyzed; (2) number of moles of growing species are conserved; (3) at least some NH_3 molecules are thermally cracked in the gas phase. Using the resulting model, the influence of growth parameters such as V/III and flow rate on AlGaN growth was determined through the dependence of the Ga and Al supersaturation. The independent parameters for the calculations included the growth conditions that were set by typical conditions for AlGaN MOCVD growth. Calculation showed a significantly lower equilibrium vapor pressure for Al (10^{-12}-10^{-16} Torr) than for Ga (10^{-4}-10^{-6} Torr). The Ga equilibrium pressure monotonously decreased with increasing V/III ratio, while NH_3 thermal cracking was more significant on the equilibrium pressure, as expected from Le Chatelier`s principle. The significant difference in the supersaturation between Ga and Al has a significant influence on the growth of ternary AlGaN compounds and need to be considered for finding appropriate and robust growth conditions at high temperatures, exceeding 1150 ºC. A processing AlGaN compositional phase diagram dependent on the typical growth conditions will be presented. In addition, experimental validation of this model with respect to Al composition, process stability and robustness will be discussed. This validation will be presented in terms of temperature and V/III ratio.

5:20pm **EM+NS-ThA10 Anomalous Hall Effect in MOCVD-grown Gadolinium-doped Gallium Nitride**, *V.G. Saravade, P. Patel, C. Ferguson, K. Yunghans, A. Ghods, C. Zhou,* ***Ian Ferguson***, Missouri University of Science and Technology

Dilute Magnetic Semiconductor (DMS) materials for spintronics applications have the potential to reduce power consumption while increasing the processing speed, integration densities and non-volatile memory, compared to the conventional semiconductor devices. While Gd-doped GaN has exhibited room temperature (RT) ferromagnetism, the Anomalous Hall Effect (AHE) has not been reported in relation to the observed magnetic properties [1, 2].

In this work, we study the AHE in MOCVD-grown Gd-doped GaN with different Gd concentrations and precursors, and investigate their magnetic properties. RT AHE along with XRD helps in determining the mechanisms responsible for the observed ferromagnetism. Our preliminary measurements showed residual R_{xy}/R_{xx} up to 10 and residual coercive field up to 50 Oe. These hysteresis curves can be caused by the ferromagnetic properties of MOCVD-grown Gd-doped GaN. Additionally, GaN (002) peak had been identified in the initial Ω-2θ XRD scans. XRD rocking curve scans with varying Ω will be performed to study, the defects that are induced by doping GaN with Gd, and their potential contribution towards ferromagnetism. AHE and XRD results of Gd-doped GaN will be compared to those of un-doped GaN to verify that the ferromagnetism is caused by Gd doping. Furthermore, the effect of temperature on the magnetic behavior of Gd-doped GaN will be analyzed using variable temperature AHE.

To our knowledge, we are the first to report the AHE in MOCVD-grown Gd-doped GaN. We consider this work to contribute towards the investigation of DMS for RT ferromagnetism and further for spintronics applications.

References

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5:40pm **EM+NS-ThA11 Valence and Conduction Band Offsets of Al_2O_3, $LaAl_2O_3$, AZO and ITO with Ga_2O_3**, ***Patrick Carey IV****, F. Ren, D. Hays, B. Gila, S.J. Pearton,* University of Florida*, S. Jang,* Dankook University, South Korea*, A. Kuramata*, Tamura Corporation, Japan

Band alignments for Al_2O_3, $LaAl_2O_3$ (LAO), Aluminum Zinc Oxide (AZO), and Indium Tin Oxide (ITO) with bulk β-Ga_2O_3 were determined by X-ray Photoelectron Spectroscopy. β-Ga_2O_3 is a direct band gap, ~4.9 eV, semiconductor, it has a very high theoretical breakdown electric field (~8 MV/cm), and is suitable for high power electronics in industrial, military applications, deep-UV photodetectors for a cut-off wavelength of 280 nm, and high temperature gas sensors. Ohmic contact with low contact resistance and gate oxides with low leakage current are essential for fabricating high performance base Ga_2O_3 electronic and optical devices. Since Ga_2O_3 has a wide energy bandgap, it is difficult to form low resistance Ohmic contact with conventional metal contact. ITO and AZO were found to have a conduction band offset of gap of -0.32 and -0.79 eV, respectively, which can be used as an intermediate layers between the metal contact and Ga_2O_3 to reduce contact resistance on Ga_2O_3-based devices. For wider energy band oxides, for use as gate oxides, sputtered LAO, atomic layer deposited (ALD) and rf-magnetron sputtered Al_2O_3 were employed. LAO was found to have a bandgap of 6.5 eV, a valence band offset of -0.21 eV, and a conduction band offset of 2.01 eV. LAO has a type II alignment and would provide excellent electron confinement, but no barrier for hole transport. Al_2O_3 was found to have a bandgap of 6.9 eV regardless of preparation method. However, the deposition method affected the band alignment. For ALD Al_2O_3, it has a has a nested (type I) gap alignment with a valence band offset of 0.07eV and a conduction band offset of 2.23 eV. While for sputtered Al_2O_3 on the same Ga_2O_3, there is a type II alignment with a valence band offset of -0.86 eV and a conduction band offset of 3.16 eV. The conduction band offsets in either case are large and provide excellent electron confinement, but the valence band offsets are smaller than desirable for limiting hole transport.

6:00pm **EM+NS-ThA12 *In Situ* Plasma Emission Spectroscopy of InN/GaN Heterostructures Grown by MEPA-MOCVD**, ***Daniel Seidlitz****, B.G. Cross, Y. Abate,* Georgia State University*, A. Hoffmann,* Technical University of Berlin, Germany*, N. Dietz*, Georgia State University

In this study, we will present results of the in-situ plasma emission spectroscopy (PES) of the plasma activated nitrogen species during the growth of GaN/InN heterostructures by MEPA-MOCVD in correlation to their optical and structural characteristics.

Indium-rich InGaN semiconductors are of high interest due to the high electron mobility which enables ultrafast electronics operating in the THz

regime. In conventional MOCVD, indium incorporation above 25 % is a challenge due to the vastly different partial pressures between InN and GaN and the lattice mismatch between the binaries. Migration enhanced plasma-assisted MOCVD is a kinetic stabilized growth surface approach to reduce the partial pressure difference between the InN and GaN. It also replaces the traditional ammonia precursor source for nitrogen through energetically controlled ionized nitrogen species (N*/NH*/NHx*), generated by a radio-frequency hollow cathode (13.56 MHz) with an output power between 50-600 W. The plasma-excited species are tailored in the gas phase and directed to the growth surface in the afterglow regime of the remote plasma utilizing the kinetic energies of the active nitrogen species to achieve a stable growth surface. Altering the process parameters like reactor pressure and nitrogen flux allows variation of the kinetic energies. A grid between the plasma source and the growth surface enables the control of the charged species reaching the growth surface and with it the electrostatic interactions in the InN/GaN growth process and the resulting layer properties. In-situ real-time plasma emission spectroscopy (PES) is used to monitor and identify the active nitrogen species close to the hollow cathode as well as near the growth surface. Comparison of the spectra could help to determine which nitrogen species promote the growth of group III- nitride materials.

Optoelectronic and structural qualities such as free carrier concentration as well as crystallinity, growth rate, the surface morphology of the GaN and InGaN films are examined using ex-situ characterization techniques (Raman, AFM, FTIR). We will present a correlation of the in-situ and ex-situ results as a function of the explored growth parameters like growth temperature, plasma power, and reactor pressure.

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