

## Electronic Materials and Photonics Division Room B116 - Session EM+TF-ThM

### Wide- and Ultra-Wide Band Gap Materials and Devices

**Moderators:** Erica Douglas, Sandia National Laboratories, Seth King, University of Wisconsin - La Crosse, Daniel Pennachio, Naval Research Laboratory

8:00am **EM+TF-ThM-1 Ga<sub>2</sub>O<sub>3</sub> and AlN for Power and RF Electronics, Grace Xing**, Cornell University **INVITED**

It's of little surprise that there has been a consistent drive toward the use of wider bandgap materials for power and RF electronics. After all, the wider the bandgap, the greater the breakdown field, opening the door to making devices with a higher breakdown voltage for the same material thickness. Furthermore, the saturation velocity of mobile carriers in ultra-scaled devices tends to be about  $1-2 \times 10^7$  cm/s in most semiconductors.

However, nature is not always that generous. Typically, a move to a wider bandgap is accompanied by more challenging doping, point defect control, ohmic contacts, quality junctions, along with difficulty in making high-quality native substrates. Ga<sub>2</sub>O<sub>3</sub> and AlN are among the promising contenders, given their large bandgaps, availability of large-size bulk substrates (>2 inches), and heterojunctions. But both lack p-type. AlN possesses high thermal conductivity – slightly worse than that of copper but Ga<sub>2</sub>O<sub>3</sub> has a low thermal conductivity – worse than that of sapphire.

Given all these promises and obstacles, is it possible to harvest all the benefits in AlN and Ga<sub>2</sub>O<sub>3</sub> and demonstrate devices that are superior to those made from SiC and GaN? I will reflect on our efforts in seeking answers to these questions in the past many years researching on power and RF devices with a focus on Ga<sub>2</sub>O<sub>3</sub> and AlN [1-6].

References:

- [1] Z. Hu *et al.*, Appl. Phys. Lett. 92 85111 (2015) Near unity ideality factor and Shockley-Read-Hall lifetime in GaN-on-GaN p-n diodes with avalanche breakdown.
- [2] W. Li *et al.*, IEEE Trans. Electron Dev. (2020) Guiding principles for trench Schottky barrier diodes based on ultrawide bandgap semiconductors: a case study in Ga<sub>2</sub>O<sub>3</sub> [<https://doi.org/10.1109/TED.2020.3003292>]
- [3] A. Hickman *et al.*, SST (2021) Next generation electronics on the ultrawide-bandgap aluminum nitride platform.
- [4] A. Green *et al.*, APL Materials (2022) Beta-gallium oxide power electronics.
- [5] E.K. Kim *et al.*, APL (2023) N-polar GaN/AlGaN/AlN HEMTs on single-crystal bulk AlN substrates.
- [6] W. Zhao *et al.*, IEEE EDL (2023) 15-GHz epitaxial AlN FBARs on SiC substrates.

8:40am **EM+TF-ThM-3 Deep UV Photoluminescence Mapping of Gallium Oxide, Matthew McCluskey**, Washington State University

Photoluminescence (PL) spectroscopy is an important method to characterize dopants and defects in gallium oxide. Features in the PL spectrum include the intrinsic UV band, blue and green bands that involve donor-acceptor pairs, and red emission due to Cr<sup>3+</sup> impurities. PL mapping with excitation wavelengths as short as 266 nm reveals the spatial distribution of these features with submicron resolution. In Czochralski-grown β-Ga<sub>2</sub>O<sub>3</sub>:Fe, the Cr<sup>3+</sup> emission intensity shows striations that are attributed due to inhomogeneities during growth. In addition to defects in the bulk, PL microscopy has revealed several specific defects on the surface. Some of these localized centers are very bright UV emitters. Raman scans of these bright emitters revealed hydrocarbon peaks, which may point toward the origin of the light emission. Samples damaged by high-intensity laser pulses show significant changes in the intensity and energy of the intrinsic UV band.

9:00am **EM+TF-ThM-4 Spatially Resolved Polymorph Conversion in Ga<sub>2</sub>O<sub>3</sub>, U. Bektas, P. Chekhonin, R. Heller, R. Hübner, M. Liedke, N. Klingner, Gregor Hlawacek**, Helmholtz Zentrum Dresden-Rossendorf, Germany  
Monoclinic galliumoxide (β-Ga<sub>2</sub>O<sub>3</sub>) is a promising wideband gap semiconductor with a bandgap of 4.7 eV and a high breakdown voltage. However, the existence of several metastable polymorphs and the immature fabrication technology limits its applications. The research is

based on the recent observation that β-Ga<sub>2</sub>O<sub>3</sub> can reliably be converted into γ-Ga<sub>2</sub>O<sub>3</sub> using high energy ion beams [1,2]. It could also be shown that the resulting γ-Ga<sub>2</sub>O<sub>3</sub> layer exhibits an exceptional tolerance towards high fluence ion beam irradiation [3].

Here, we use focused ion beam (FIB) induced processing to convert β-Ga<sub>2</sub>O<sub>3</sub> into γ-Ga<sub>2</sub>O<sub>3</sub> in a spatially controlled way. We employ focused Ne ions from a helium ion microscope (HIM) and liquid metal alloy ion sources (LMAIS) based FIB with Co, Si, and In to induce the polymorph conversion. Electron backscatter diffraction (EBSD), transmission electron microscopy (TEM) and atomic force microscopy (AFM) are used to confirm, in a spatially resolved way, the successful polymorph conversion. From the obtained EBSD data the orientation relationship between the irradiated and unirradiated material is resolved. Broadbeam irradiated reference samples have been used to corroborate these results with channeling Rutherford backscattering spectrometry (c-RBS), X-ray diffraction (XRD) and Doppler broadening variable energy positron annihilation spectroscopy (DB-VEPAS) results. The obtained crystal structure and defect distribution data supports the model suggested for the conversion mechanism [3].

This research is supported by the tax funds on the basis of the budget passed by the Saxonian state parliament in Germany and the COST Action CA19140 FIT4NANO <https://www.fit4nano.eu/>.

- [1] A. Azarov, C. Baziotti, Disorder-Induced Ordering in Gallium Oxide Polymorphs, Phys. Rev. Lett. 128 (2022), 015704.
- [2] J. Garcia-Fernandez, S.B. Kleldby, Formation of γ-Ga<sub>2</sub>O<sub>3</sub> by ion implantation: Polymorphic phase transformation of β-Ga<sub>2</sub>O<sub>3</sub>, Appl. Phys. Lett. 121 (2022), 191601.
- [3] A. Azarov, J. G. Fernández, J. Zhao, F. Djurabekova, H. He, R. He, Ø. Prytz, L. Vines, U. Bektas, P. Chekhonin, N. Klingner, G. Hlawacek, A. Kuznetsov, Universal radiation tolerant semiconductor (2023), doi:10.48550/ARXIV.2303.13114.

9:20am **EM+TF-ThM-5 Low-Temperature Epitaxy and in-situ Doping of Ultrawide Bandgap Ga<sub>2</sub>O<sub>3</sub> Films via Hollow-Cathode Plasma-ALD, S. Ilhom, A. Mohammad, N. Ibrahimli, J. Grasso, B. Willis**, University of Connecticut;

A. Okyay, OkyayTech Inc; **Necmi Biyikli**, University of Connecticut  
Wide and ultrawide bandgap (WBG/UWBG) semiconductors make the backbone of high-power high-frequency electronics, used in electric vehicles, 5G and beyond wireless communication systems, and smart power grids. Gallium oxide (Ga<sub>2</sub>O<sub>3</sub>) is an emerging UWBG semiconductor showing superior material properties particularly ideal for harsh environments (high temperature, high-energy radiation, corrosion) applications. Reducing the growth and doping process temperatures for Ga<sub>2</sub>O<sub>3</sub> would potentially enable a wider integration platform towards post-CMOS integration and flexible electronics.

Herein, we report on the low-temperature as-grown crystalline β-Ga<sub>2</sub>O<sub>3</sub> films on Si, glass, and sapphire via hollow-cathode plasma-assisted atomic layer deposition (HCP-ALD). The films were deposited using triethylgallium (TEG) and Ar/O<sub>2</sub> plasma as metal precursor and oxygen co-reactant, respectively. Additionally, we have employed *in situ* atomic layer doping to n-type dope Ga<sub>2</sub>O<sub>3</sub> films where tris-dimethylaminosilane (TDMAS) and tetrakis-dimethylaminotin(IV) (TDMASn) were utilized as the dopant precursors. Growth experiments have been performed at 240 °C under 50 W rf-plasma power. The doping process was carried out via both supercycle (ABC-type ALD-cycle) and co-dosing methods. Additionally, each unit ALD-cycle was followed by an *in-situ* Ar-plasma annealing treatment, which consisted of Ar-plasma exposure for 20 seconds at 250 W rf-power. Both *in-situ* and *ex-situ* ellipsometry were employed to measure the thickness and optical properties of the Ga<sub>2</sub>O<sub>3</sub> samples. X-ray diffraction (XRD) of the sample on sapphire revealed epitaxial Ga<sub>2</sub>O<sub>3</sub> films with monoclinic *b*-phase, while GIXRD analyses of the samples grown on Si and glass displayed *b*-phase polycrystalline films. HR-STEM imaging and EDX elemental analysis confirmed the epitaxial relationship of the films grown on sapphire substrates and displayed successful incorporation of dopant elements. Preliminary electrical conductivity measurements showed highly resistive samples. Therefore, *ex-situ* thermal annealing studies are carried out to explore dopant activation processes. Further studies from our XPS characterizations will provide additional insight about the chemical bonding states of the dopant species. A significant effort will be devoted for the comparison of Si and Sn-doping strategies and potential suggestions will be provided to overcome the challenges in achieving device quality undoped and doped Ga<sub>2</sub>O<sub>3</sub> layers at low processing temperatures.

# Thursday Morning, November 9, 2023

9:40am **EM+TF-ThM-6 Growth of Metastable Ga<sub>2</sub>O<sub>3</sub> Epitaxial Films Using Metalorganic Chemical Vapor Deposition and Halide Vapor Phase Epitaxy**, *Jingyu Tang, K. Jiang, M. Weiler, M. Moneck, R. Davis, L. Porter*, Carnegie Mellon University

Gallium oxide (Ga<sub>2</sub>O<sub>3</sub>) is an ultra-wide bandgap semiconductor of interest for electronics that can operate in extreme conditions, such as high power, high temperature and radiation exposure. β-Ga<sub>2</sub>O<sub>3</sub> is thermodynamically stable at atmospheric conditions up to its melting point and is the phase produced in melt-grown, single-crystal substrates. However, epitaxial films of metastable polymorphs of Ga<sub>2</sub>O<sub>3</sub> are also of interest because they possess unique properties – such as piezoelectricity, ferroelectricity, or ferromagnetism – that could lead to new types of heterostructure devices. We report here the growth and characterization of both mixed-phase and phase-pure epitaxial films of each of the metastable polymorphs: κ(ε) and γ using metalorganic chemical vapor deposition (MOCVD); and α, κ and γ using halide vapor phase epitaxy (HVPE). The effect of variables, such as substrate temperature, will be reported, as will the use of different substrates / orientations to produce phase-pure epitaxial films of α-, κ-, and γ-Ga<sub>2</sub>O<sub>3</sub> in the same growth runs. The microstructure, composition, and morphology of the films and film/substrate interfaces were characterized using x-ray diffraction (XRD) θ-2θ scans, rocking curves, and φ scans; scanning electron microscopy (SEM); and high-resolution cross-section transmission electron microscopy (TEM) with energy dispersive x-ray (EDX) analysis.

11:00am **EM+TF-ThM-10 AlGa<sub>N</sub>/Ga<sub>N</sub> HEMTs with Submicron Gates for High-Frequency Operation in Harsh Space Environments**, *Isabel Harrysson Rodrigues, M. Rais-Zadeh*, Jet Propulsion Laboratory, California Institute of Technology

Indium aluminum nitride/gallium nitride high electron mobility transistors (AlGa<sub>N</sub>/Ga<sub>N</sub> HEMTs) offer excellent properties such as high electron mobility and wide bandgap, making them ideal for high-frequency and high-power applications, in harsh environments. The wide band gap of the AlGa<sub>N</sub>/Ga<sub>N</sub> heterostructure offers inherent radiation tolerance compared to traditional Si microelectronics. Owing to the advantageous two-dimensional electron gas, AlGa<sub>N</sub>/Ga<sub>N</sub> HEMTs can provide increased sensitivity, fast response time, and low noise levels while withstanding extreme temperatures, radiation, and vibrations found in space. Its robustness and reliability make it ideal for long-term missions, ensuring accurate and uninterrupted sensing and detection in difficult space conditions. DC operation has been achieved for AlGa<sub>N</sub>/Ga<sub>N</sub> HEMTs with various larger gate dimensions. Separate studies have shown successful operation of AlGa<sub>N</sub>/Ga<sub>N</sub> HEMTs at high temperatures reaching 1000°C. However, in achieving high-frequency operation, the device geometry must be size-optimized from large-area to scaled gate lengths in the submicron regime. RF analysis at both room temperature and high temperature is a necessary next step to determine the merits of these devices for extreme environment applications where these devices have advantages over other semiconductor technologies. In this work, the performance of AlGa<sub>N</sub>/Ga<sub>N</sub> HEMTs are optimized by reducing the gate length toward high-frequency operation in harsh space environments, with specific applications in on-board rover communications and for in situ readout of sensor data. The geometry schemes were chosen during the design phase, and the microfabrication process, metallization, and passivation materials were carefully evaluated. These results are promising for further testing, e.g., radiation tolerance, high temperatures, and monolithic circuit integration. The presented devices have an advantage over traditional heterogeneous integration strategies for GaN devices which requires silicon ASICs that, without cooling, cannot operate in high-temperature environments.

11:20am **EM+TF-ThM-11 Selected-Area P-Type Doping of GaN Using Focused-Ion Beams**, *Sam Frisone*, University of Michigan; *M. Titze*, A. Katzenmeyer, Sandia National Lab; *B. Li*, Yale University; *A. Flores*, Sandia National Lab; *Y. Wang*, Los Alamos National Laboratory; *R. Goldman*, University of Michigan; *E. Biejolec*, Sandia National Lab; *J. Han*, Yale University

Due to their potential for high breakdown voltage and low on-resistance, GaN-based electronic devices are promising for high-power and high-frequency electronics. Vertical GaN p-i-n devices are expected to offer improved thermal management and reduced leakage current in comparison to their lateral counterparts; however, typical etching and regrowth processes introduce interfacial impurities that limit control of dopant profiles. Thus, a strategy for both vertical and lateral dopant selectivity, without the need for etching and regrowth, is essential for the development of high-quality vertical GaN devices. Here, we report on Mg doping using a liquid-metal ion source (LMIS) in a mass-selecting focused-

ion-beam (FIB) column. For these studies, an unintentionally doped (UID) 3.6μm GaN layer is grown by metalorganic chemical vapor deposition on n-type GaN. In preparation for FIB implantation, the UID GaN layer was patterned with an array of Au/Ti markers. Checkerboard patterns consisting of alternating 70x70 and 50x50μm squares, with and without Mg FIB implantation, were prepared using a Mg-doped AuSi eutectic as the LMIS. The ion energies were set to 70keV, resulting in a most probable ion implantation depth of 70nm; seven ion fluences ranging from 10<sup>12</sup>-10<sup>15</sup> cm<sup>-2</sup>, corresponding to Mg concentrations of 10<sup>16</sup>-10<sup>19</sup> cm<sup>-3</sup>, were used. To examine the activation of Mg dopants in GaN, we compare the pristine and implanted regions before and after rapid-thermal processing (RTP). A distinct checkerboard pattern is observed in secondary electron (SE) images, with reduced SE image intensities in the implanted regions compared to the pristine regions. Following removal of the Au/Ti markers and 30 seconds of RTP at 1100°C, the checkerboard pattern is reduced in the vicinity of the four lowest ion fluences. For all regions, cathodoluminescence (CL) spectroscopy reveals GaN near-band edge (NBE) emissions at 3.4eV. The intensity of NBE emission is highest in the pristine regions, especially those in the vicinity of the two lowest ion fluences. Furthermore, in pristine regions adjacent to the two lowest ion fluences we observe CL emissions at 2.85eV and 2.2eV. As discussed in [1], we attribute these emissions to impurity-related donor-acceptor pairs and yellow luminescence, respectively. The reduced SE image intensity and limited CL emission in the vicinity of the highest ion fluences suggest incomplete Mg dopant activation. The influence of additional RTP on the dopant activation will be discussed. [1] 10.1016/j.nanoen.2022.107689

11:40am **EM+TF-ThM-12 Epitaxial Growth and Characterization of High ScN Fraction ScAlN on NbN and SiC**, *Matthew Hardy, S. Katzer, A. Lang, E. Jin, N. Nepal, B. Downey, V. Gokhale, V. Wheeler*, U.S. Naval Research Laboratory

ScAlN thin films have attracted significant attention due to their factor of five increase in piezoresponse over AlN for Sc<sub>0.43</sub>Al<sub>0.57</sub>N. Integration of metallic epitaxial NbN with ScAlN using molecular beam epitaxy (MBE) enables a pathway towards a highly conductive lower electrode while preserving high crystal quality even in relatively thin ScAlN films suitable for use at or above X-band frequencies. Maintaining phase-pure and high crystal quality Sc<sub>x</sub>Al<sub>1-x</sub>N at high x is critical to improve resonator bandwidth and reduce insertion loss.

In this work, we show the importance of the ScAlN nucleation layer to the final crystal quality and anomalously oriented grain (AOG) density of MBE-grown ScAlN films on SiC and NbN/SiC. Starting the ScAlN growth with a Sc<sub>0.32</sub>Al<sub>0.68</sub>N layer can suppress the rock-salt ScAlN material at the nucleation interface, as seen by reflection high-energy electron diffraction (RHEED) and transmission electron diffraction (TEM). Nucleation using a linear composition grade from Sc<sub>0.32</sub>Al<sub>0.68</sub>N to Sc<sub>0.40</sub>Al<sub>0.60</sub>N over 100 nm leads to further improvements in the RHEED pattern, including a narrowing of the spots early in the growth, as well as elimination of remaining ring-like character in the final RHEED pattern after an additional 40 nm of growth, resulting in an X-ray diffraction (XRD) FWHM as low as 1.22° for ScAlN films grown on SiC. TEM shows near elimination of cubic grains that otherwise form in the initial layers of the Sc<sub>0.40</sub>Al<sub>0.60</sub>N. The grade thickness can be reduced to 25 nm (with the remaining 125 nm Sc<sub>0.40</sub>Al<sub>0.60</sub>N) without degrading the XRD FWHM or RHEED pattern, increasing the average ScN fraction from 0.373 to 0.393. Finally, a 500-nm-total-thickness sample (100 nm Sc<sub>0.32</sub>Al<sub>0.68</sub>N → Sc<sub>0.40</sub>Al<sub>0.60</sub>N, 400 nm Sc<sub>0.40</sub>Al<sub>0.60</sub>N) was grown to show the impact of defect annihilation in thicker films, resulting in a reduction of XRD FWHM to 0.89°. The improved layer initiation shows that more gradual changes in surface energy and strain reduces the nucleation of undesirable cubic grains, and may point to a general strategy for elimination of anomalous grains in high ScN fraction ScAlN.

Employing a similar growth approach and using a novel two-step AlN interlayer enables integration of ScAlN on an NbN epitaxial metal lower electrode. Growth conditions to first encapsulate the NbN layer, and then provide a smooth surface for ScAlN nucleation are critical to minimize degradation in XRD FWHM or AOG density. ScAlN on NbN structures enable characterization of the ScAlN dielectric constant and electromechanical coupling coefficient (k<sub>t</sub><sup>2</sup>). A dielectric constant of 25 and k<sub>t</sub><sup>2</sup> of 27% was extracted for Sc<sub>0.32</sub>Al<sub>0.68</sub>N from a Sc<sub>0.32</sub>Al<sub>0.68</sub>N/AlN/NbN/SiC sample.

# Thursday Morning, November 9, 2023

12:00pm **EM+TF-ThM-13 Novel Graphene and SiC Epitaxy to Enable Film Transfer**, *Daniel Pennachio, J. Hajzus, A. Lang*, US Naval Research Laboratory; *R. Stroud*, Former employee of US Naval Research Laboratory; *R. Myers-Ward*, US Naval Research Laboratory

Remote epitaxy (RE) is a promising technique for epitaxial film transfer that utilizes graphene as a release layer [1]. Graphene grown on SiC(0001) substrates through Si sublimation or through propane chemical vapor deposition (CVD) is an ideal platform for remote epitaxy of wide bandgap (WBG) semiconductors as there is no need for a graphene transfer step, mitigating contamination or defects that can complicate the remote epitaxy process. In addition, the graphene/SiC materials system is compatible with commercially-viable WBG semiconductor growth and processing, making it a suitable choice for scalable future development. A challenge to utilizing SiC is that CVD growth is typically conducted using high-temperature hydrogen-based chemistries that could damage or remove graphene. This study investigates the effect of alternative low-H<sub>2</sub> CVD growth conditions on SiC/graphene/SiC(0001) remote epitaxy that may reduce damage to the graphene barrier. In addition, graphene preparation and associated surface morphology is varied to explore its effect on SiC epilayer formation.

For this work, the effects of Ar:H<sub>2</sub> process gas flow ratio, growth precursor C/Si ratio, and growth temperature on hot-wall CVD SiC RE crystalline quality were investigated. Both semi-insulating nominally on-axis 6H-SiC(0001) and n-type 4° off-axis 4H-SiC(0001) substrates were used to produce different surface morphologies and graphene layer numbers. Nomarski optical microscopy, scanning electron microscopy, and atomic force microscopy found CVD deposition at 1620°C with Ar/H<sub>2</sub> ratios <20/5 slm, and C/Si ratios <1.55 to have the smoothest surface morphology and fewest polytype inclusions. Substrates with offcuts <0.1° from SiC(0001) exhibited lower epilayer macrostep density but showed evidence of polytype impurities and 3D growth at C/Si ratios > 1.0. RE on EG/4H-SiC(0001) substrates with a 4° off-cut from SiC[0001] had a wider parameter range resulting in single-crystalline growth compared to growth on the nominally on-axis substrates despite growth of >1 monolayer EG on these substrates. This study found smooth, single-crystalline polytype-pure SiC(0001) epilayers on EG substrates could be grown using predominantly Ar carrier gas, with H<sub>2</sub> concentrations as low as ~2%. Through this study, optimal SiC RE growth conditions are suggested for a balance of EG survivability and SiC film morphology.

[1] Kim, Y., Cruz, S., Lee, K. et al. Nature 544, 340–343 (2017).

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