International Workshop on Gallium Oxide and Related Materials (IWGO-6)
Room ESJ 0202 - Session IWGO-MoM2

Epitaxial Growth and Doping Control I

Moderators: Oliver Bierwagen, Paul-Drude Institute for Solid State Electronics, **Yuichi Oshima**, National Institute for Materials Science

11:05am **IWGO-MoM2-38 Toward 150mm Ga2O3 Epitaxy by HVPE***, **Jacob Leach**, Caroline Reilly, Heather Splawn,* KYMA TECHNOLOGIES, INC **INVITED**

The key to realizing the full potential of Ga$_2$O$_3$-based devices for medium voltage (>1kV) power switching applications lies in large part in the ability to grow thick (>20 microns) and simultaneously lightly doped (<1x10^{16} cm^{-3}) drift layers with high crystalline quality. To date, the only option for preparing such thick layers on diameter-scalable (001)-oriented freestanding Ga$_2$O$_3$ substrates is halide vapor phase deposition (HVPE). Our previous work focused on the development of thick homoepitaxial layers on 2" substrates by HVPE which could be controllably doped throughout the ranges of interest for power electronics device designers, i.e. from ~5x10^{15} cm^{-3} to ~3x10^{16} cm^{-3} [1]. In this work, we report on the growth of commercially relevant Ga$_2$O$_3$ epilayers grown on 100mm and 150mm substrates using HVPE. Figures below show a photograph of an as-grown ~20µm thick epilayer as well as a N_D-N_A free carrier concentration map showing good doping control in the range of ~1-2x10^{16} cm^{-3} over a 100mm substrate. Initial results from similar epilayers grown on 150mm substrates will be presented as well as an outlook on the commercial landscape for thick epilayers of Ga$_2$O$_3$.

Acknowledgements

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[1] Leach et al. GOX 2025, Salt Lake City UT, USA, 5 August 2025.

11:30am **IWGO-MoM2-43 MOCVD Growth of (011) β-Ga$_2$O$_3$ up to 20 µm: Defect Optimization and Device Impact***, **Md Mosarof Hossain Sarkar**, Dong su Yu,* The Ohio State University*; Jiawei Liu,* SUNY at Buffalo*; Sadikul Alam, Mehidi Hassan,* The Ohio State University*; Yuki Ueda, Chia-Hung Lin, Kohei Sasaki,* Novel Crystal Technology, Japan*; Jinwoo Hwang,* The Ohio State University*; Uttam Singisetti,* SUNY at Buffalo*; Hongping Zhao,* The Ohio State University

β-Ga$_2$O$_3$ has emerged as a promising semiconductor for vertical power electronics. However, achieving high-quality thick β-Ga$_2$O$_3$ drift layers with smooth surface morphology and well-controlled low doping remains a long-standing challenge. In HVPE growth of thick (001) β-Ga$_2$O$_3$, post-growth chemical–mechanical polishing (CMP) is typically required to achieve adequate surface smoothness for device processing.

In this study, (011) β-Ga$_2$O$_3$ films up to 20 µm thick were grown on (011) β-Ga$_2$O$_3$ substrates at growth rates of 2.86–5.5 µm/h. Atomic force microscopy (AFM) measurements revealed smooth surfaces with RMS roughness of 0.48–1.05 nm (5x5 µm^2), among the lowest reported for comparable thicknesses. X-ray diffraction (XRD) confirmed high crystalline quality, with rocking curve FWHM of 13.6 arcsec (on-axis) and 29.2 arcsec (off-axis), indicating low threading dislocation density. Dent-type defects increased with thickness but were mitigated by incorporating a buffer layer. Secondary ion mass spectrometry (SIMS) indicated low background levels of C, H, and Si, near the detection limit.

Substrate pre-treatment and growth conditions were optimized to suppress dent-type defects. The incorporation of acid treatment, in-situ annealing, buffer layers, and pulse-flow growth layer led to a reduction of defect density by over an order of magnitude. Schottky barrier diodes (SBDs) were fabricated on the MOCVD-grown (011) β-Ga$_2$O$_3$ drift layers, as shown in Fig. 1(a). The forward J–V characteristics exhibit near-ideal behavior with an ideality factor of $\eta = 1.02$, Schottky barrier height of $\phi_B = 1.47$ eV, and turn-on voltage of $V_{on} = 1.11$ V (defined at 1 A/cm^2). The forward current density exceeded 1250 A/cm^2 at 5 V. Reverse-bias measurements yielded a breakdown voltage of ~640–740 V, which is expected to be further improved through optimized field-management designs in future work.

Overall, these results demonstrate that high-quality thick (011) β-Ga$_2$O$_3$ drift layers can be achieved by MOCVD with effective defect control, enabling strong potential for high-performance vertical power devices.

11:45am **IWGO-MoM2-46 Colossal Bandgaps: Growing Si-Doped α-(AlxGa1-x)$_2$O$_3$ Films with Eg ≤ 7 eV with s-MBE***, **Jacob Steele**, Debaditya Bhattacharya, Kazuki Nomoto,* Cornell University*; M. K. Indika Senevirathna,* Clark Atlanta University*; Huili "Grace" Xing, Debdeep Jena, Darrell G. Schlom,* Cornell University

One emerging ultrawide bandgap material that is closely related to Ga$_2$O$_3$ is α-(Al$_x$Ga$_{1-x}$)$_2$O$_3$, which has a tunable E_g ranging 5.4 – 8.6 eV. Despite theory predicting silicon to be a shallow n type donor over the range of 5.4 – 7.5 eV[1], achieving active donors has proven to be extremely difficult. This challenge has led to only molecular-beam epitaxy (MBE)[2], metal-organic chemical vapor deposition (MOCVD)[3], and mist chemical vapor deposition (CVD)[4] having produced any conductive films with $x > 0$.

We previously have demonstrated that an uncommon variant of MBE, suboxide MBE (*S*-MBE), can be utilized to grow α-(Al$_x$Ga$_{1-x}$)$_2$O$_3$ with excellent structural quality[5], as well as α-Ga$_2$O$_3$ with record electronic properties[6]. In this work, we report a multistep *S*-MBE technique that reliably produces conductive Si-doped α-(Al$_x$Ga$_{1-x}$)$_2$O$_3$ thin films with *S*-MBE. The technique produces conductive α-(Al$_x$Ga$_{1-x}$)$_2$O$_3$ thin films with $x \leq 0.58$ ($E_g = 7.0$ eV).

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[2] H. Okumura, and J.B. Varley, Jpn. J. Appl. Phys. **63**(7),075502 (2024).

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[4] G.T. Dang, et al. 2020, AIP Adv. **10**, 115019

[5] J. Steele, et al., APL Mater. **12**(4), 041113 (2024).

[6] J. Steele, et al. APL Mater. **13**, 101117 (2025).

12:00pm **IWGO-MoM2-49 Fast Step-Flow Growth on Highly Offcut (100) Ga2O3 Substrates***, **M Brooks Tellekamp**,* National Renewable Energy Laboratory*; Drew Haven, David Joyce,* Luxium Solutions*; Henry Garland, John Mangum,* National Renewable Energy Laboratory*; Kevin Schulte, Anna Sacchi, Matthew Young, Andriy Zakutayev,* national renewable Energy Laboratory

The (100) surface of Ga$_2$O$_3$ is highly desirable from a device and epitaxy standpoint – bulk growth of (100) material is more scalable than (010), the surface is nearly lattice-matched to p-type partner NiO, and Al$_2$O$_3$ incorporates at higher concentrations without phase separation. More importantly, the impact ionization coefficients along the [100] direction are minimized while the dielectric constant is maximized, leading to the highest possible critical fields. This is advantageous compared to the current state of the art, (001), due to reduced surface defects and increased possible breakdown voltage. However, the epitaxial growth rate on (100) surfaces is less than 10% of other faces due to weak bonding and favorable desorption, and on-axis (100) growth easily forms twin domains. Recent demonstrations have shown growth rate improvements from 0.4 nm/min to 1.5 nm/min by growing on (100) wafers that are offcut 6° in the -c direction.[1] These films show step-flow growth from (20-1) step-edges and high electron mobility due to suppressed twins. Despite these exciting results, offcuts greater than 6° have not been explored due to the waste associated with grinding and polishing large offcuts.

In this talk we will discuss the molecular beam epitaxy (MBE) growth and properties of β-Ga$_2$O$_3$ grown on (100) substrates offcut in the -c direction up to 13.4°. These large offcuts are enabled by edge-fed film-defined growth (EFG) where the offcut is grown into the surface by pulling the crystal through the EFG die with the seed crystal rotated by the desired offcut angle. We will demonstrate that 13.4° offcut substrates still exhibit a terraced (100) surface, and that a >10x increase (>5 nm/min) in growth rate is achieved. Despite the large offcut angle we will demonstrate step-flow growth with RMS roughness values below 2 nm RMS, even after 600 nm of growth. As previously reported on lower offcuts, we observe reversal of substrate twin domains around the (001) direction at the substrate-epilayer interface. This increase in growth rate, along with careful control of impurity levels, leads to record-low (by MBE) unintentional doping densities of < 2E15 cm^{-3} on 13.4° offcut wafers and < 5E15 cm^{-3} on 11.1° offcut wafers. We will also demonstrate (Al$_x$Ga$_{1-x}$)$_2$O$_3$ films grown on highly offcut substrates are monoclinic up to x = 0.33. This work establishes highly offcut (100) β-Ga$_2$O$_3$ as a viable and scalable alternative substrate orientation for power electronic devices.

12:15pm **IWGO-MoM2-52 Record High Mobility with Observation of Quantum Oscillations at Low Temperature for 2DEGs in MOCVD Grown β-$(Al_xGa_{1-x})_2O_3$/β-Ga_2O_3 Heterostructures***, **Joshua Buontempo**, Cameron Gorsak, Pushpanshu Tripathi, Hari Nair,* Cornell University

The ultra-wide bandgap (∼ 4.8 eV) and high estimated breakdown field strength (8 MV/cm) of β-Ga_2O_3 make it a promising material for radio frequency applications [1]. One of the main material limitations that hinders device performance is a low maximum room temperature mobility (∼ 200 cm^2/Vs) [2]. This is further exacerbated once dopants are introduced into the β-Ga_2O_3 lattice, as scattering from ionized and neutral impurities further reduces the electron mobility [2, 3]. One approach to increase the carrier mobility, while retaining high carrier densities, is to implement modulation doping in a heterostructure. The spatial separation of the impurity atoms from the charge carriers in a triangular quantum well results in the formation of a high mobility 2-dimensional electron gas (2DEG) channel [4, 5].

In this work, we utilize triethylaluminum (TEAl) and triethylgallium (TEGa) for the source of Al and Ga, respectively, to grow β-$(Al_xGa_{1-x})_2O_3$/β-Ga_2O_3 heterostructures by MOCVD. TEAl and TEGa pyrolyze via β-hydrogen elimination [6], enabling minimal carbon incorporation at a relatively low substrate temperature of 650 °C, which is essential for mitigating the formation of compensating gallium vacancies while maintaining high crystalline quality and low surface roughness. As-grown films exhibit room-temperature mobilities as high as 165 cm^2/Vs at a sheet density of ∼ 1.8×10^{12} cm^{-2}. The films exhibits record low-temperature mobility for a β-$(Al_xGa_{1-x})_2O_3$/β-Ga_2O_3 2DEG as high ∼ 2914 cm^2/Vs at 45 K.

Additionally, from Shubnikov–de Haas (SdH) oscillations below 5 K, we extract a 2DEG density of 1.7×10^{12} cm^{-2}, in agreement with transport data. We extract a cyclotron effective mass, $m^* = 0.308 \pm 0.004\ m_e$, which agrees with the calculated conduction band non-parabolicity in β-$(Al_xGa_{1-x})_2O_3$/β-Ga_2O_3 and the estimated position of E_F above the conduction band minimum [7]. This work affirms the viability of MOCVD using TEAl and TEGa for growing high-quality gallium oxide–based heterostructures.

References

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