## Epitaxial Growth
## Room Bansal Atrium - Session EG-MoP

### Epitaxial Growth Poster Session I

**EG-MoP-1 A Study of the Critical Thickness for Phase Transition of α-Gallium Oxide Grown on Sapphire Substrates by MOCVD**, *Cheng-Han Lee, C. Gorsak, H. Nair,* Department of Materials Science and Engineering, Cornell University

The ultra-wide bandgap semiconductor material α-Ga₂O₃ exhibits promising potential for applications in next-generation high-power electronics and deep-ultraviolet photodetectors. Its large bandgap of 5.3 eV enables a high breakdown voltage and a potentially high Baliga's figure of merit while its rhombohedral corundum structure allows heteroepitaxy of α-Ga₂O₃ on inexpensive isostructural sapphire substrate. One of the major challenges is achieving thick, phase-pure α-Ga₂O₃ films using metal-organic chemical vapor deposition (MOCVD) due to the metastable nature of α-Ga₂O₃. Metastable α-Ga₂O₃ has a strong tendency to revert back to the thermodynamically stable monoclinic β-Ga₂O₃ phase. This gives rise to the natural question: Can epitaxial growth of single-phase α-Ga₂O₃ with high crystalline quality be achieved via MOCVD and how does the critical thickness of α-Ga₂O₃ films depend on MOCVD growth parameters and different surface orientations of sapphire substrates, and what is the mechanism for phase transformation to β-Ga₂O₃?

In this study, we investigate the critical thickness for structural phase transition of MOCVD-grown α-Ga₂O₃ epitaxial thin films grown on c-, m-, r-, and a-plane sapphire substrates. To ensure high crystallinity and to suppress defect generation, we develop a two-step growth method in which a 10-nm-thick α-Ga₂O₃ low-temperature nucleation layer was deposited at 600°C at a low growth rate of 0.4 μm/hr, followed by a high temperature growth of Ga₂O₃ epilayer with thickness ranging from 100 nm to 1600 nm at 600~800°C with a higher growth rate of 0.7~1.0 μm/hr. X-Ray diffraction (XRD) was utilized to confirm the phase purity of α-Ga₂O₃ films and to evaluate crystalline quality based on rocking curve Full-Width-at Half Maximum (FWHM). We successfully demonstrated that single-phase, highly-crystalline α-Ga₂O₃ films with thickness ~400 nm can be achieved on m-plane sapphire substrate through a low-pressure, low-temperature, and high growth rate heteroepitaxial growth, resulting in one of the highest α-Ga₂O₃ critical thickness ever reported on m-plane α-Al₂O₃ via MOCVD.

This work highlights the importance of selecting suitable differently oriented sapphire substrates for the growth of phase-pure α-Ga₂O₃ epitaxial thin films using MOCVD. We pursue to further increase the critical thickness and aim to delineate the mechanism for phase transformation of α-Ga₂O₃. Thicker films and controllable doping of α-Ga₂O₃ thin films can potentially pave the way for the fabrication of α-Ga₂O₃ based high-power electronic devices.

**EG-MoP-2 Epitaxial Growth of β-Ga₂O₃ Films on Mgo Substrate via Mist Chemical Vapor Deposition Method**, *Takumi Ikenoue,* Kyoto University, Cronell University, Japan*; Y. Cho, V. Protasenko, C. Savant, B. Cromer,* Cornell University*; M. Miyake, T. Hirato,* Kyoto University, Japan*; M. Thompson, D. Jena, H. Xing,* Cornell University

Gallium oxide (Ga₂O₃) is expected to be a promising material for power devices due to its wide bandgap and high Baliga figure of merit. Various methods of epitaxial growth have been explored for β-Ga₂O₃, including growth on MgO substrates which possess a larger bandgap than β-Ga₂O₃ and sufficient insulation. MgO has the same crystal structure as NiO, which is expected to be a p-type wide-gap oxide semiconductor, and has a small lattice mismatch, making it the most promising candidate for the substrate for epitaxial growth of NiO. Consequently, the growth of β-Ga₂O₃ on MgO is important, particularly for the development of devices that combine NiO and β-Ga₂O₃. We previously conducted a study on the growth of NiO on MgO substrates using mist chemical vapor deposition (CVD). This oxide film growth technique utilizes a solution as a source under atmospheric pressure and is known for its high quality and productivity. By using this method, we showed the ability to not only produce high-quality NiO(001) single crystals on MgO(001), but also achieve conductivity control by using Li as a dopant. The growth of β-Ga₂O₃ on MgO would lead directly to heterojunction formation with NiO, which has almost the same lattice constant as MgO. Therefore, in this study, we report the growth of β-Ga₂O₃ on MgO(001) substrates using the mist CVD method.

Prior to growth, MgO substrates were ultrasonically cleaned with acetone and methanol. The precursor used for β-Ga₂O₃ growth was gallium acetylacetonate, which was diluted in deionized water at a concentration of 0.020 mol/L. Hydrochloric acid was added for complete dissolution. Growth temperature and time were set at 600 ˚C and 6 minutes respectively.

XRR measurements determined the film thickness to be 80.6 nm with a growth rate of 0.806 μm/h, which is comparable to HVPE. Peaks from β-Ga₂O₃ (400) and β-Ga₂O₃ (600) were observed by the XRD 2θ scan, indicating that (100)-oriented β-Ga₂O₃ was grown. It should be noted that the peak of γ-Ga₂O₃ (400) (at 2θ=43.93°), which was observed in the growth of β-Ga₂O₃ on MgO using PLD and MOCVD, was not observed. With no γ-Ga₂O₃ phase at the interface between MgO and β-Ga₂O₃, it may be possible to fabricate a sharp interface in β-Ga₂O₃ growth on MgO and p-NiMgO. The full width at half maximum of the ωrocking curve from β-Ga₂O₃ (400) was 145 arcsec, indicating high-quality crystal growth. From the φ scan, the in-plane orientation was determined to be β-Ga₂O₃ (100)[001] ∥ MgO (001)[110]. In addition, the RSM roughness of the 5x5 μm² AFM image was 0.74 nm.

**EG-MoP-3 Fluid Analysis of MIST-CVD Chamber for Uniformity Improvement in Gallium Oxide Epitaxial Growth**, *Jungyeop Hong, Y. Jung, D. Chun, J. Park, N. Joo, T. Kim,* Hyundai Motor Company, Republic of Korea

Gallium oxide has emerged as a promising material for high-performance electric vehicle and UV application applications. Among the various crystal phases of gallium oxide, the alpha phase has the widest band gap, making it suitable for manufacturing high voltage semiconductor devices. However, the alpha phase cannot be grown by homo-epitaxy, and the method of growing on a foreign substrate is mainly employed.

This paper focuses on the deposition of gallium oxide on wafers and highlights the limitation of the current maximum wafer size to 2 inches. To enable mass productivity, there is a need for equipment and process technologies that can accommodate larger wafer sizes for deposition. The research presented in this study aims to address this challenge by proposing solutions that can potentially contribute to the development of more efficient and cost-effective production processes for gallium oxide-based devices.

The study investigated the challenge of achieving stable uniformity in Ga2O3 epi grown on a 4-inch substrate compared to a 2-inch substrate. To overcome this issue, the authors proposed a fluid analysis of the MIST-CVD chamber to identify potential improvements for achieving better uniformity. This research can contribute to the development of Ga2O3 epi with higher uniformity and quality on larger substrates, which is crucial for its practical applications.

We conducted a study on growing Ga2O3 epi layers on a 4-inch substrate using MIST-CVD equipment. To achieve uniform growth of the epi on the 4-inch substrate, they evaluated the distribution level of the mist using fluid analysis methods. The chamber was modeled, and the mist distribution level was numerically interpreted under various conditions using fluid analysis tools. The optimal epi growth conditions with high mist distribution level and uniformity were derived based on the results. Growth technique was developed to obtain process reproducibility and excellent epitaxy quality even on a 4-inch wafer.

The research demonstrated the up-scale growth of high-quality Ga2O3 epi-layers on sapphire substrates, which could have potential applications in high-power and high-frequency electronic devices. To improve the uniformity of the large substrate, Our group modeled the sample position and gas flow in the Chamber and optimized the process conditions to achieve excellent uniformity. To verify the improvement in the uniformity of the epitaxial deposition, measurements using an Ellipsometer and XRD were performed.

**EG-MoP-6 The Effect of Excess Ga on Electron Transport in β-Ga₂O₃ Grown via Plasma Assisted Molecular Beam Epitaxy**, *Thaddeus Asel, B. Noesges, Y. Kim, A. Neal, S. Mou,* Air Force Research Laboratory, Materials and Manufacturing Directorate, USA

Since the first demonstration of β-Ga₂O₃ based devices, there has been significant work done developing epitaxial growth methods for high quality β-Ga₂O₃ films. Improvement in the mobility of epitaxial films has been demonstrated in recent years. Additionally, the quantification of defect states in thin films has been performed for several growth techniques, including molecular beam epitaxy (MBE). However, there has yet to be a systematic study of the relationship between the β-Ga₂O₃ growth parameters, the electronic transport properties, and the defects present in β-Ga₂O₃ films grown via MBE. In this work we investigate the effect of excess Ga beam flux on the electronic properties of β-Ga₂O₃ films grown via MBE. Utilizing temperature dependent Hall Effect measurements and a self-

consistent fitting of the temperature dependent carrier density and mobility data, we are able to quantify the concentration defect states, including compensating acceptors, deep level impurities, and unintentional donors, present in the epitaxial films. The Ga beam flux can control the oxygen to Ga ratio present in the chamber as our oxygen is held constant for each growth run. This allows for growths that occur in the "oxygen rich" regime where the amount of Ga supplied limits the growth rate and the "gallium rich" regime where the amount of O supplied limits the growth rate. In both regimes the formation of the volatile suboxide $Ga_2O$ occurs, but in the gallium rich regime, the desorption of $Ga_2O$ causes a lower growth rate than that seen in the oxygen rich regime, due to the excess of Ga presence preventing the second reaction step in $Ga_2O_3$ growth. Two preliminary samples were grown in the gallium rich (Ga Beam Flux = $1 \times 10^{-7}$ Torr) and oxygen rich (Ga Beam Flux = $6 \times 10^{-8}$ Torr) regimes. The samples had different doping densities of $4.25 \times 10^{17}$ cm$^{-3}$ in the gallium rich sample and $2.60 \times 10^{17}$ cm$^{-3}$ in the oxygen rich sample, this discrepancy is due to an inaccuracy in the Si doping source. The acceptor concentration in the gallium rich sample was calculated to be $7.26 \times 10^{16}$ cm$^{-3}$ and $4.50 \times 10^{15}$ cm$^{-3}$ in the oxygen rich sample, a factor of 16 different based on the Ga overpressure. This is likely due to Ga vacancies that can form during the desorption of $Ga_2O$ during growth. These results indicate that there is significant impact on the electron transport properties of $\beta$-Ga$_{-2}$O$_3$ when there is excess Ga present during the growth, and that optimization of growth parameters is needed to optimize the electronic properties of MBE grown $\beta$-Ga$_{-2}$O$_3$.

**EG-MoP-7 Low-Pressure Chemical Vapor Deposition of Ultrawide Bandgap LiGa$_5$O$_8$ Thin Films**, *Kaitian Zhang, L. Meng, H. Huang,* The Ohio State University; *J. Sarker,* University of Buffalo, SUNY; *A. Bhuiyan,* The Ohio State University; *B. Mazumder,* University of Buffalo, SUNY; *J. Hwang, H. Zhao,* The Ohio State University

LiGaO$_2$ represents an ultrawide band gap semiconductor with an energy gap of 5.8 eV. It is considered as a group I-III-VI$_2$ counterpart of the group II-VI ZnO, and has an orthorhombic crystal structure. The ground state β-LiGaO$_2$ has a Pna2$_1$ space group. It has recently been predicted that LiGaO$_2$ is n-type dopable with Si or Ge and the possible p-type doping is under investigation. LiGaO$_2$ has been considered for piezoelectric and nonlinear optical applications in the past. Bulk growth of single-crystal LiGaO$_2$ has been studied as closely lattice-matched substrate (a = 5.407 Å, b = 6.405 Å and c = 5.021 Å) for GaN epitaxy. However, thin film growth of LiGaO$_2$ is still at an early stage with only PLD growth of LiGaO$_2$ on ZnO template was reported.

In this work, low pressure chemical deposition (LPCVD) of LiGaO$_2$ on various substrates were studied. C-plane sapphire, (010) and (001) LiGaO$_2$ substrates were used in this study. High purity Ga pallets, LiCl powder and O$_2$ were used as the precursors whereas Ar was used as the carrier gas. The growth temperature was kept at 900 °C. From a series of material characterization, the film grown on top of the (001) LiGaO$_2$ substrate is stabilized with a spinel-cubic structure LiGa$_5$O$_8$ with a lattice constant of 8.203 Å and space group P4_33-2 (Ga in both tetrahedral and octahedral sites). The spinel-cubic crystal structure of the LiGa$_5$O$_8$ film was confirmed from the atomic resolution HAADF STEM image and selected area electron diffraction (SAED) pattern. Additionally, the atom probe tomography (APT) measurement on the same sample confirmed a uniform Li distribution and a near-stoichiometric ratio of ~1:5:8 for Li/Ga/O.

LiGa$_5$O$_8$ has been studied as a phosphor host material when doped with transition metal and rare earth elements. To the best of our knowledge, this work represents the first experimental demonstration of thin film growth of pure LiGa$_5$O$_8$. Recent theoretical calculations suggest that LiGa$_5$O$_8$ has an indirect bandgap of approximately 5.7 eV with the direct gap about 0.1 eV higher, which renders LiGa$_5$O$_8$ a potential ultrawide bandgap semiconductor for power electronics applications.

In conclusion, this investigation explored the LPCVD growth of LiGaO$_2$ thin films on c-sapphire and LiGaO$_2$ substrates. The results revealed a successful growth of LiGa$_5$O$_8$ film on (001) LiGaO$_2$ substrate. Comprehensive growth conditions still need to be mapped to determine the correlation between the growth condition, substrate selection and stabilization of crystal structure of LiGa$_x$O$_y$.

**EG-MoP-8 Controlling Si Dopant Profiles in n-type $\beta$-Gallium Oxide**, *Brenton Noesges, Y. Kim, A. Neal, S. Mou, T. Asel,* Air Force Research Laboratory, Materials and Manufacturing Directorate, USA

Oxidation of dopant sources affects dopant vapor pressures which can impact dopant profile uniformity in $\beta$-Ga$_2$O$_3$ grown via plasma-assisted molecular beam epitaxy (PAMBE).[1,2] In this work, we will focus on optimizing uniform dopant profiles in the low Si doping regime (<10$^{18}$ cm$^{-3}$) of $\beta$-Ga$_2$O$_3$ films since Si doping concentrations show a gradient, increasing toward the surface of $\beta$-Ga$_2$O$_3$ thin films. Si concentrations of ~3x10$^{17}$ cm$^{-3}$ are achievable as demonstrated by secondary ion mass spectroscopy (SIMS). Capacitance-voltage (CV) measurements to extract carrier concentrations agree well with Si concentrations observed in SIMS. We will also look at another aspect of Si incorporation in $\beta$-Ga$_2$O$_3$ that needs consideration when using traditional effusion cells as a Si dopant source. Previous work in PAMBE $\beta$-Ga$_2$O$_3$ growth demonstrated the importance of oxygen plasma power on controlling the background amount of Si present in $\beta$-Ga$_2$O$_3$ films.[3] In this work, we continued to explore sources of unintentional Si accumulation during the PAMBE growth process. The presence of Si at the interface between $\beta$-Ga$_2$O$_3$ substrate and film provides a parasitic conduction channel which is problematic for device performance. Attempts have been made to remove this Si at $\beta$-Ga$_2$O$_3$ interfaces via etching. Our results indicate that removing interfacial Si may not be as simple since Si can re-accumulate during PAMBE processes, thus limiting the effectiveness of pre-growth surface treatments. We created a test sample for SIMS simulating the effects of exposing clean $\beta$-Ga$_2$O$_3$ surfaces to potential sources of Si in a PAMBE system including quartz plasma bulb and dopant Si effusion cells. Exposure to only quartz plasma bulb did not produce Si accumulation at the surface. On the other hand, a growth interrupt that exposed a fresh $\beta$-Ga$_2$O$_3$ to the hot Si source for several minutes produced Si accumulation equal to that of the interfacial Si between substrate and film. These results demonstrate that removing Si prior to loading into PAMBE may be inadequate to remove interfacial Si since Si can be re-introduced from the Si dopant cell during pre-deposition stages like plasma stabilization. This work and results point toward important challenges and potential solutions when creating Si-doped $\beta$-Ga$_2$O$_3$ thin films.

[1] Kalarickal, N.K., et al., *Appl. Phys. Lett.* **115**, 152106 (2019).

[2] McCandless, J.P., et al. *Appl. Phys. Lett.* **121**, 072108 (2022).

[3] Asel, T. J., et al., *J. Vac. Sci. Technol.* A **38**, 043403 (2020).

**EG-MoP-9 Silicon-doped $\beta$-Ga2O3 Films Grown at 1 μm/h by Suboxide Molecular-Beam Epitaxy**, *Kathy Azizie, F. Hensling, C. Gorsak,* Cornell University; *Y. Kim,* Air Force Research Laboratory; *N. Pieczulewski,* Cornell University; *D. Dryden,* Air Force Research Laboratory; *M. Senevirathna, S. Coye,* Clark Atlanta University; *S. Shang,* Penn State University; *J. Steele, P. Vogt, N. Parker, Y. Birkhölzer, J. McCandless, D. Jena, H. Xing,* Cornell University; *Z. Liu,* Penn State University; *M. Williams,* Clark Atlanta University; *A. Green,* Air Force Research Laboratory; *D. Schlom,* Cornell University

We report the use of suboxide molecular-beam epitaxy (S-MBE) to grow $\beta$-Ga$_2$O$_3$ at a growth rate of ~1 μm/h with control of the silicon doping concentration from 5*10$^{16}$ to 10$^{19}$ cm$^{-3}$. In S-MBE, pre-oxidized gallium in the form of a molecular beam that is 99.98% Ga$_2$O, i.e., gallium suboxide, is supplied. Directly supplying Ga$_2$O to the growth surface bypasses the rate-limiting first step of the two-step reaction mechanism involved in the growth of $\beta$-Ga$_2$O$_3$ by conventional MBE. As a result, a growth rate of ~1 μm/h is readily achieved at a relatively low growth temperature ($T_{sub} \approx 525$ °C), resulting in films with high structural perfection and smooth surfaces (rms roughness of < 2 nm on ~1 μm thick films). Silicon-containing oxide sources (SiO and SiO$_2$) producing an SiO suboxide molecular beam are used to dope the $\beta$–Ga$_2$O$_3$ layers. Temperature-dependent Hall effect measurements on a 1 μm thick film with a mobile carrier concentration of 2.7*10$^{17}$ cm$^{-3}$ reveal a room-temperature mobility of 124 cm$^2$ V$^{-1}$ s$^{-1}$ that increases to 627 cm$^2$ V$^{-1}$ s$^{-1}$ at 76 K; the silicon dopants are found to exhibit an activation energy of 27 meV. We also demonstrate working MESFETs made from these silicon-doped $\beta$-Ga$_2$O$_3$ films grown by S-MBE at growth rates of ~1 μm/h.

**EG-MoP-10 Epitaxial Growth of Metastable Ga₂O₃ Polymorphs Using MOCVD and HVPE**, *Jingyu Tang, M. Moneck, M. Weiler, K. Jiang, R. Davis, L. Porter,* Carnegie Mellon University

In recent years, there has been an increasing interest in the growth and electronic properties of metastable $Ga_2O_3$ polymorphs, e.g., $\kappa$-$Ga_2O_3$ with its high predicted spontaneous polarization as a potential ferroelectric material and $\alpha$-$Ga_2O_3$ with its wider bandgap and ability to alloy with $\alpha$-$Al_2O_3$. The metastable $\kappa$-$Ga_2O_3$ phase can be grown in epitaxial film form on substrates such as 4H/6H-SiC, $Al_2O_3$, AlN, GaN using vapor phase techniques. The $\kappa$-$Ga_2O_3$ films reported in the literature have varying degrees of phase purity and commonly contain three in-plane rotational domains, although there are some reports of suppressed rotational domains or increased domain sizes when grown on lattice-matched $GaFeO_3$ substrates[1], patterned sapphire[2] and $SiH_4$ gas introduction[3]. $\alpha$-$Ga_2O_3$ films with high dislocation densities have been commonly grown on c-plane sapphire as indicated by the broader full-width-at-half-maxima (FWHM) of the X-ray rocking curves (XRC) of the tilted planes. Film growth techniques such as epitaxial lateral overgrowth[4], depositing buffer layers[5] have been implemented to reduce the dislocation density. In this study, nominally phase-pure $\alpha$-$Ga_2O_3$ and $\kappa$-$Ga_2O_3$ epitaxial films were grown on vicinal a-plane and c-plane sapphire substrates, respectively, at Carnegie Mellon University using halide vapor phase epitaxy (HVPE) and/or metalorganic chemical vapor deposition (MOCVD). Phase and microstructural characterization studies were conducted using high-resolution X-ray diffraction (HR-XRD), scanning electron microscopy (SEM), and transmission electron microscopy (TEM). The growth of $\kappa$-$Ga_2O_3$ using MOCVD[6] revealed the presence of a 20-60 nm thick transition layer containing a mixture of $\beta$- and $\gamma$-$Ga_2O_3$ near the interface. In contrast, there was no detectable $\beta$ peak or even a $\beta$ shoulder in the $\kappa$-$Ga_2O_3$ films grown by HVPE. The FWHM of the (004) $\kappa$-$Ga_2O_3$ XRC for the HVPE film was 5x more narrow than that of the MOCVD film with respective values of 0.11° and 0.49°. Comparable FWHM values in the literature for $\kappa$-$Ga_2O_3$ are 0.16° to 0.82°[3,7,8]. Whereas. $\alpha$-$Ga_2O_3$ has been difficult to produce using MOCVD, nominally phase-pure (11-20) $\alpha$-$Ga_2O_3$ films with exceptionally low FWHM for (11-20) = 0.034° are readily produced at 650°C using HVPE. In summary, our findings indicate that HVPE growth leads to nominally phase-pure $\alpha$-$Ga_2O_3$ and $\kappa$-$Ga_2O_3$ epitaxial films with narrow XRCs, and offers promising avenues for further investigation of the properties of metastable $Ga_2O_3$ phases.

**EG-MoP-11 Pulsed Laser Deposition of α-Ga₂O₃ on M-Plane Al₂O₃: Growth Regime, Growth Process and Structural Properties**, *Clemens Petersen,* University Leipzig, Felix Bloch Institute for Solid State Physics, Semiconductor Physics Group, Leipzig, Germany*; S. Vogt, H. von Wenckstern, M. Grundmann,* University Leipzig, Felix Bloch Institute for Solid State Physics, Semiconductor Physics Group, Germany

Due to its wide band gap of 4.6 eV - 5.6 eV and large predicted breakdown field of 8 MV cm$^{-1}$ [1], much attention is drawn to the ultra-wide bandgap semiconductor $Ga_2O_3$ for applications in high-power devices. However, besides the well-studied thermodynamically stable monoclinic $\beta$-phase of $Ga_2O_3$, the metastable $\alpha$-polymorph with corundum structure is rapidly gaining interest in the scientific community. Since it is isostructural to $\alpha$-$Al_2O_3$, growth of layers with high structural quality on cost-efficient sapphire substrates is feasible. In particular, m-plane sapphire facilitates the growth of the corundum phase by suppressing c-plane facets on which the $\beta$-phase favorably crystallizes [2]. Further, Sn-doped $\alpha$-$Ga_2O_3$ thin films grown on m-plane sapphire show electron mobilities of up to 65 cm$^2$ V$^{-1}$ s$^{-1}$, which is three times higher than what can be achieved on c-plane cut substrates as reported by Akaiwa *et al.* [3]. To our knowledge, a systematic study of the growth of $Ga_2O_3$ on m-plane sapphire by pulsed laser deposition (PLD) has not been published to date.

We present phase-pure $\alpha$-$Ga_2O_3$ thin films with high surface quality and crystallinity grown on m-plane sapphire using PLD [4]. Therefore, the influence of growth temperature, oxygen background pressure, and film thickness on structural properties is investigated to determine the growth window for phase-pure $\alpha$-$Ga_2O_3$. Samples were analyzed using X-ray diffraction, atomic force microscopy, and spectroscopic ellipsometry measurements. A distinct growth window for phase-pure (10.0)-oriented $\alpha$-$Ga_2O_3$ at growth temperatures above 450°C and low oxygen partial pressures $p$(O2) of 3×10$^{-4}$ mbar is identified. It was found that for thicker layers (> 200 nm) the growth of monoclinic $\beta$-$Ga_2O_3$ is promoted. This is likely induced by the c-facets of the $\alpha$-$Ga_2O_3$ grains, leading to a (010) oriented island growth corroborated by stripe-like features in atomic force microscopy scans and a corresponding in-plane orientation confirmed by x-ray diffraction $\phi$-scans. For oxygen partial pressures above 3×10$^{-4}$ mbar and growth temperatures below 530°C, the formation of mixed (10.0) $\alpha$-

$Ga_2O_3$ and spinel-defective (110) $\gamma$-$Ga_2O_3$, manifesting as inclusions, was observed independently of the layer thickness. A corresponding phase diagram for $Ga_2O_3$ growth on m-plane sapphire by PLD is presented.

1. Higashiwaki *et al.*, Appl. Phys. Lett., Vol. 100, 013504 (2012)

2. Jinno *et al.*, Sc. Advances, Vol. 7, No. 2, eabd5891 (2021)

3. Akaiwa *et al.*, pss (a), Vol. 217, No. 3, 1900632 (2020)

4. Petersen *et al.*, APL Materials, accepted manuscript, (2023)

**EG-MoP-14 High-Quality Power Device Grade β-Ga₂O₃ on 4H-SiC via Metal Organic Chemical Vapor Deposition**, *I. Sanyal, A. Nandi,* **Martin Kuball,** University of Bristol, UK

$Ga_2O_3$ suffers from low thermal conductivity which would translate into excessive device temperatures. Integration with high thermal conductivity materials is, therefore, essential to explore. We report epitaxial growth of high material quality $\beta$-$Ga_2O_3$ on 4H-SiC (0001) substrates using MOCVD. Recent reports indicated $\beta$-$Ga_2O_3$ growth on 4H-SiC at a deposition temperature of 650 °C using LPCVD, resulting in rms surface roughness of 2.25 nm and FWHM of 1.3°, and at 700 °C using liquid-injection MOCVD with rms surface roughness of 8 nm. However, we observed formation of incomplete misoriented particles when the layer was grown at a temperature between 650 °C to 750 °C as shown in fig 1. Two steps modified growth method was then adopted where the nucleation layer was grown at 750 °C followed by a buffer layer grown at various temperatures from 750 to 950 °C. Three samples namely S1, S2 and S3 were compared to understand the growth mechanism. S1 and S2 are identical except the bulk layer where the growth temperature was 920 °C and 950 °C respectively. S1 shows partly coalesced surface with misoriented grains or nano-crystallites as shown in fig.2. Whereas, S2 forms fully coalesced surface without any pseudohexagonal domains as shown in fig. 3. XRD 2θ-ω scan confirms $\beta$-polymorph of $Ga_2O_3$ with dominant peak in (-201) direction and FWHM of 0.9°. One of the challenges in growing $\beta$-$Ga_2O_3$ on SiC substrate with O$_2$ source at high temperature is the formation of amorphous $SiO_2$ layer on the growth surface that results in poor crystal quality. Si-terminated 4H-SiC/ $\beta$-$Ga_2O_3$interface is highly sensitive to O$_2$ due to its lowest migration energy. O-terminated $\beta$-$Ga_2O_3$ in (-201) direction and Si-terminated 4H-SiC in (0001) direction offer lowest relaxation energy and thus highest stability by forming covalent bond between Si-O at the interface. Furthermore, the nucleation layer grown at lower temperatures is polycrystalline in nature with a high density of defects that propagate into the top layer. Instead of growing a thin nucleation layer at a fixed lower temperature, we implemented a new 'ramp-growth' technique in S3 where the growth of the nucleation layer starts at 780 °C and the temperature linearly increases to 950 °C within three minutes followed by the growth of the buffer layer at 950 °C. As can be seen in fig. 4, the surface roughness reduced to 3 nm with FWHM as low as 0.79°, comparable to the most mature $\beta$-$Ga_2O_3$ heteroepitaxy on sapphire using MOCVD, greatly advanced to currently available $Ga_2O_3$ on SiC, paving the way for the development of high voltage device fabrication with improved thermal property.

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