International Workshop on Gallium Oxide and Related Materials (IWGO-6)

Room ESJ Concourse - Session IWGO-MoP

IWGO Poster Session I

Moderators: Esmat Farzana, Iowa State University, **Katie Gann**, Naval Research Laboratory

IWGO-MoP-1 Anisotropic Wet Etching of β-Ga2O3 using TMAH*, Takayoshi Oshima,* NIMS, Japan

This study demonstrates advanced surface treatment and microfabrication techniques for β-Ga_2O_3 using TMAH etching. (i) Mild etching of (001) substrates with 2.38 wt% TMAH (a standard photolithographic developer) at 25–40 °C transforms relatively rough, CMP-finished surfaces into atomically flat step-and-terrace morphologies [1]. On (010) substrates, aggressive etching with 25 wt% TMAH at 90 °C reveals significant crystallographic anisotropy. (ii) Specifically, pronounced lateral etching along the [001] direction facilitates the undercutting of dry-etched mesa structures to form β-Ga2O3/air-gap structures, such as air-bridges and cantilevers [2] . (iii) Furthermore, the high etch resistance perpendicular to the (−201) plane allows for the refinement of dry-etched trenches, transforming rough, slanted sidewalls into smooth, vertical (−201) facets [3]. These results provide straightforward pathways for the surface preparation, the development of high-performance β-Ga_2O_3 MEMS and fin/trench-based power devices.

This work was supported by ARIM program (JPMXP1225NM5079)andJSPS KAKENHI (JP24K01368).

[1] T. Oshima, Jpn. J. Appl. Phys. **64**, 088001 (2025).[2] T. Oshima, Appl. Phys. Express **18**, 116501 (2025).

[3] T. Oshima, AIP Advances**16**, 025145 (2026).

IWGO-MoP-2 Electrical Characterization of 1D P–N Heterojunctions with Axial and Core–Shell Architectures*, Roman Yatskiv,* Institute of Photonics and Electronics of the Czech Academy of Sciences, Czechia

One-dimensional wide-bandgap heterostructures have attracted increasing interest in recent years because of their significant potential applications in future optoelectronic devices. We developed a novel technique to investigate the electrical properties of individual nanorods [1], nanostripes [2], or axial/core–shell p–n junctions [3,4] using a nanomanipulator in the chamber of a scanning electron microscope. In contrast to conventional approaches, this method eliminates the use of extensive processing chemistry and allows the observation of morphological changes in situ during electrical characterisation.

Figure 1 (a) individual CuI/ZnO core–shell heterojunction in contact with a gold electrode; **(b)** experimental setup for the electrical measurement of a single core–shell CuI/ZnO NR heterojunction; **(c)** representative room-temperature I–V characteristics of an individual CuI/ZnO core–shell heterojunction.

1. S. Tiagulskyi, O. Černohorský, N. Bašinová, R. Yatskiv, J. Grym, Materials Research Bulletin, **164** (2023) 112286.
2. P. Wojnar, S. Chusnutdinow, A. Kaleta, M. Aleszkiewicz, S. Kret, J.Z. Domagala, P. Ciepielewski, R. Yatskiv, S. Tiagulskyi, J. Suffczyński, A. Suchocki, T. Wojtowicz, Nanoscale, **16** (2024) 19477-19484.
3. S. Tiagulskyi, R. Yatskiv, H. Faitová, Š. Kučerová, J. Vaniš, J. Grym, Materials Science in Semiconductor Processing, **107** (2020) 104808.
4. S. Tiagulskyi, R. Yatskiv, M. Sobanska, K. Olszewski, Z.R. Zytkiewicz, J. Grym, Nanoscale, **17** (2025) 8111-8117.

+Author for correspondence: yatskiv@ufe.cz

IWGO-MoP-4 Metal-Catalyst-Dependent Growth of β-Ga_2O_3 Nanowires on Sapphire for Solar-Blind UV Photodetectors*, JungBok Lee,* *MinSeok Jang, HeeJin Kim, JuEun An, HoJun Lee,* Pusan National University, Republic of Korea

β-Ga_2O_3 has emerged as a promising ultra-wide-bandgap semiconductor for solar-blind ultraviolet (UV) photodetectors owing to its large bandgap, high breakdown field, and excellent thermal stability In this study, β-Ga_2O_3 nanowires were synthesized on sapphire substrates by Pulsed Laser Deposition (PLD) using different metal catalysts, including Au, Ag, Cu, Ni, and Ti, in order to investigate the influence of catalyst species on nanowire growth and device performance.SEM analysis revealed clear catalyst-dependent differences in nanowire density, morphology, and size distribution, indicating that the choice of metal catalyst strongly affects nucleation and growth behavior. Structural characterization by XRD and Raman spectroscopy confirmed the formation of β-Ga_2O_3 nanowires on sapphire substrates. Based on the as-grown nanowire networks, metal–semiconductor–metal (MSM) photodetectors were fabricated and evaluated under UV illumination. The devices exhibited a distinct photoresponse under 254 nm excitation, while the response under longer-wavelength UV illumination was relatively weaker, demonstrating selective solar-blind UV sensitivity.Among the investigated catalysts, the Ag-assisted β-Ga_2O_3 nanowires showed the most enhanced photoresponse and the highest photo-to-dark current contrast, indicating superior photodetection behavior compared with the other catalyst-assisted samples. The improved performance is attributed to catalyst-dependent variations in nanowire growth characteristics and interfacial charge transport. These results demonstrate that metal-catalyst engineering is an effective route for tuning β-Ga_2O_3 nanowire growth and improving the performance of solar-blind UV photodetectors, providing useful insight for future wide-bandgap oxide optoelectronic devices.

IWGO-MoP-5 Epitaxial Growth of Si Doped β-$(InxGa1-x)_2O_3$ Thin Films on (010) β-Ga_2O_3 Substrates*, Aoi Saito,* Kyoto Institute of Technology, Japan*; Hiroki Miyake,* MIRISE Technologies Corporation, Japan*; Hiroyuki Nishinaka,* Kyoto Institute of Technology, Japan

β-Ga_2O_3 has a large bandgap of approximately 4.8 eV and bulk substrates can be fabricated by melt-growth methods, making it a promising candidate for power device applications. Whereas β-$(Al_xGa_{1-x})_2O_3$/β-Ga_2O_3 heterostructures have been the primary focus for β-Ga_2O_3-based HEMT structures [1], β-$(Al_xGa_{1-x})_2O_3$/β-$(In_yGa_{1-y})_2O_3$ heterostructures have recently attracted attention due tothe expectation of a larger band offset. Nevertheless, reports on the high-quality growth of β-$(In_xGa_{1-x})_2O_3$ remain scarce, and understanding its physical properties is essential for HEMT applications. In particular, since β-$(In_xGa_{1-x})_2O_3$ serves as the channel layer, understanding its electrical properties is important. In this study, Si doping in β-$(In_xGa_{1-x})_2O_3$ was investigated using the mist CVD method, which has been successfully used for crystal growth in our group [2].

Figure 1 shows the XRD 2θ–ω measurement results for samples with In concentrations of 1.8 and 3 vol.% in the solution. As shown in Fig. 1, a diffraction peak accompanied by clear fringes was observed for the sample with an In concentration of 1.8 vol.%, indicating the growth of a thin film with high crystallinity. In contrast, when the In concentration was 3 vol.%, the fringes disappeared, and degradation of crystallinity due to lattice relaxation was observed. Figure 2 shows the electron mobility as a function of In concentration with [Si]/[Ga]=0.1 at.%. As shown in Fig. 2, the mobility decreases with increasing In concentration, indicating that the In composition notably influences the carrier transport properties, likely due to alloy scattering.

[1] Zhang et al., Appl. Phys. Lett. 112, 173502 (2018).

[2] H. Nishinaka, et al., Sci. Technol. Adv. Mater. 25 (2024).

IWGO-MoP-6 Dependence of Substrate Orientation the β-Ga_2O_3 Single Crystal Layer Grown by the Flux Method*, Kentaro Ishida,* *Toshinori Taishi,* Shinshu University, Japan

β-Ga_2O_3 is one of the most promising wide-bandgap semiconductor materials, with a bandgap 4.5 times wider and a breakdown voltage 25 times higher than that of silicon. Since it melts at atmospheric pressure, it is possible to grow low-cost bulk single crystals. Furthermore, device fabrication requires epitaxial growth, a technique for growing thin films on a substrate. Currently, epitaxial growth of β-Ga_2O_3 is primarily performed using vapor-phase methods such as HVPE. In recent years, the manufacture of certain high-voltage power devices has required thick epitaxial layers of β-Ga_2O_3. In this study, the solution growth of β-Ga_2O_3 using fluxes composed of MoO_3 alone or with the addition of Li_2CO_3 was investigated.

IWGO-MoP-7 Characterization of β-Ga2O3 Epitaxial Layers Using Time-Resolved Photoluminescence*, Mahiro Ishikawa,* *Takuma Ishihara, Kazuki Shimazoe,* Nagoya Institute of Technology, Japan*; Kohei Sasaki,* Novel Crystal Technology, Japan*; Masashi Kato,* Nagoya Institute of Technology, Japan

β-Ga_2O_3 has an ultrawide bandgap and has been attracting attention as a next-generation power-semiconductor device material [1]. To ensure reliability in of β-Ga_2O_3 devices, it is important to investigate the impact of defects. We investigated evaluation of β-Ga_2O_3 epitaxial wafer using photoluminescence (PL), which is non-destructive, non-contact technique.

(001) oriented β-Ga_2O_3wafers with epitaxial layer thickness of 5, 10 or 15 μm were used as samples. For evaluation, PL spectra and time-resolved PL (TR-PL) measurements were carried out using a 266 nm laser under the conditions of a pulse width of 1 ns and an excitation light intensity of 0.6 mW. These measurements were conducted both of epitaxial layer (Epi side) and substrate (Sub side) sides.

Figure 1 shows PL spectra the samples.For Sub side, a weaker emission was observed compared to those from Epi side for all the samples.On Epi side, the thicker the epitaxial layer, the stronger the light emission. The sample with an epitaxial layer thickness of 15 μm exhibited emission at wavelengths of approximately 500 nm and 560 nm, but none was observed in the samples with epitaxial layers of 5 and 10 μm.Figure 2 shows TR-PL decay curves. The TR-PL decays were faster on Sub side than on Epi side. The decays can be broadly divided into two components: fast decay with a small time constant, and the proportion of the slow decay component in Epi side depends on the epitaxial layer thickness. These results demonstrate that the time constant of the slow component would reflect crystalline quality of the epitaxial layers.

This paper is based on results obtained from a project, JPNP22007, commissioned by the New Energy and Industrial Technology Development Organization (NEDO).

Figure 1. PL spectra

Figure 2. TR-PL decay curves

[1] M. Higashiwaki: Phys. Status. Solidi. Rapid. Res. Lett. Vol15, Issue11, 5 August (2021)

+ Author for correspondence: cnj13011@ict.nitech.ac.jp [mailto:cnj13011@ict.nitech.ac.jp]

IWGO-MoP-8 Crack-Free Dicing of β-Ga2O3 Substrates*, Michael Liao,* APEX Microdevices*; Mark Goorsky,* University of California Los Angeles*; Piyush Shah,* APEX Microdevices

It is widely known that β-Ga_2O_3 substrates are mechanically fragile and cleaves easily along the (100) and (001) planes. Dicing by wafer sawing β-Ga_2O_3 substrates into coupons, dies, or chips has been reported to be a challenging task as edges of β-Ga_2O_3 are susceptible to cracking. The damaged edges from wafer sawing cracks and in some cases distort the substrate so severely that a significant area adjacent to the edge becomes unusable for either epitaxy or wafer bonding. In the case of (001) and (100) substrates, the surface also delaminates at uncontrolled depths along the thickness of the substrate upon cracking at the edges. We demonstrate successful crack-free dicing for various orientations of β-Ga_2O_3 substrates by employing pulsed UV laser dicing. The edges of wafer-saw coupons are structurally characterized and directly compared to edges of laser diced coupons, primarily the impact of each edge type on direct wafer bonding yield and exfoliation via light-atom ion implantation. Laser diced coupons produce sharp, clean edges that do not distort the substrate that would reduce wafer bonding yield. In fact, entire ~cm scale, laser-diced β-Ga_2O_3 coupons yield ~100% fully bonded areas when bonded to 4H-SiC substrates including areas up to the edge of the sample. On the other hand, cracks and delamination from wire sawed edges hinder wafer bonding altogether. Interestingly, wafer saw edges and cracks greatly impact the nucleation mechanics of light-atom ion implantation for the exfoliation and transfer of thin films. The cracks and damage induced by the wafer saw process serve as nucleation sites for the implanted light atoms to nucleate and grow to induce surface blistering or exfoliation (which would have induced layer transfer if bonded prior to annealing). However, these surface blisters appear much earlier than expected compared to the blisters in the rest of the uncracked bulk material. Control over the timing and uniformity of exfoliation is important for producing consistent thin-film β-Ga_2O_3 composite substrates. Mitigating damage and lattice distortion at substrate edges are important for either subsequent coupon processing or for dicing dies or chips from processed wafers.

The authors acknowledge the support from Air Force SBIR Phase II program. TPOC Dr. Thaddeus Asel.

IWGO-MoP-9 Silicon Implantation Doping for Channel Definition of UID Alpha and Beta Ga_2O_3 Lateral MESFET Transistors*, Aniol Vellvehí i Llovet,* Institut de microelectrònica de Barcelona (IMB-CNM-CSIC), Spain*; Amador Perez Tomas Perez Tomas,* Institut de Microelectrònica de Barcelona (IMB-CNM-CSIC), Spain

Ion implantation is a key technique for achieving local, CMOS–compatible doping profiles in Ga_2O_3 power devices. This approach has been proven in β–Ga_2O_3, but its implementation in α–Ga_2O_3 remains challenging due to the limited thermal stability of the α-phase[1]. Extending this process to α–Ga_2O_3 is particularly attractive due to its wider bandgap (~5.3 eV) and a potential critical electric field of ~10 MV/cm, compared to ~8 MV/cm in the β–phase[2], [3]. In this work, the same MESFET fabrication flow was applied to both alpha and beta-Ga2O3 in order to directly compare their compatibility with ion–implantation–based channel engineering and to identify material–dependent limitations. The α–phase samples consisted of 200 nm of α–Ga_2O_3 grown and stabilized on m–plane sapphire, while the β–phase samples consisted of 500 nm of β–Ga_2O_3 grown on (-201) ?-Ga2O3 substrates. Si implantation defined the channel region, and an Al_2O_3 cap layer was deposited before annealing to protect the surface and preserve the α–phase [4]. After activation, the cap was removed from the S/D contact regions and Ti/Au metallization was used to complete the devices. A Si+ implantation was used also to decrease the contact resistance under the source/drain metallization. In β–Ga_2O_3, Si donors were successfully activated after annealing at 950 °C, yielding functional lateral MESFETs with reproducible performance. In contrast, α–Ga_2O_3 required a wide annealing study from 500 °C to 1100 °C to balance donor activation with phase stability. The Al_2O_3 cap layer helped to preserve the α–phase up to approximately 700 °C, but this temperature was still insufficient to activate the implanted Si donors. When annealing above this limit, where activation would nominally occur (~900 °C) [5], the α–layer underwent a rapid α–to–β transformation accompanied by structural degradation. This prevented any electrical conduction through the implanted region and ultimately inhibited the free carrier control for operational α–Ga_2O_3 MESFETs via ion implantation. In summary, these results confirm the robustness of implanted–channel engineering in β–Ga_2O_3, while highlighting the fundamental limitations of ion-implantation-based channel engineering in α–Ga_2O_3 due to its limited thermal stability.

IWGO-MoP-10 Temperature-dependent Characteristics of HVPE-grown β-Ga_2O_3 Schottky Contacts with Different Metals*, Eito Hatayama,* *Kazutaka Kanegae, Hajime Takayama, Michihiro Shintani, Hiroyuki Nishinaka,* Kyoto Institute of Technology, Japan

β-Ga_2O_3 is a promising material for next-generation low-power switching devices due to its high breakdown electric field. Understanding the temperature dependence of carrier transport and Schottky barrier properties is crucial for practical device operation and reliability. We investigated the electrical characteristics of HVPE-grown β-Ga_2O_3 vertical Schottky diodes (SBDs) using different Schottky electrodes from 95 K to 408 K.

Si-doped n-type (001) β-Ga_2O_3 homoepitaxial layers, with a net donor density of 4×10^{16} cm^{-3}, were grown via halide vapor phase epitaxy on an n^+-type substrate. Ni and Cu Schottky electrodes were formed on the epitaxial surface. *C-V* and *I-V* characteristics of the SBDs were evaluated. The Schottky barrier heights (ϕ_{B0}) was determined from *C-V* characteristics, while the ideality factor (n) and the apparent Schottky barrier height (ϕ_B) were extracted from *I-V* characteristics using thermionic emission (TE) models.

The temperature dependence of ϕ_{B0} for Ni ($\phi_{B0,Ni}$) and Cu ($\phi_{B0,Cu}$) are evaluated. At each temperature, $\phi_{B0,Ni}$ was ~0.3 eV higher than $\phi_{B0,Cu}$, consistent with the difference in their work functions. Extracted temperature coefficient (α) for $\phi_{B0,Ni}$ and $\phi_{B0,Cu}$ were -5.9×10^{-4} and -7.0×10^{-4} eV/K, respectively. The obtained coefficients are consistent with the typical values reported for other metals (such as Pt and Ni), confirming that they reflect the intrinsic temperature dependence of the bandgap.

As for the carrier transport, n approached unity above approximately 200 K, confirming TE dominance. Below 200 K, n increases while ϕ_B decreases with decreasing temperature. Specifically, at around 100 K, n reached 2.58 for Ni and 1.57 for Cu. The onset temperatures for the increase in n and decrease in ϕ_B were lower for Cu than for Ni, reflecting the difference in their work function. However, deviations at lower temperatures seem to suggest that considering tunneling and/or patch effects is necessary.

IWGO-MoP-11 Effect of Ion Charge and Implantation Dosage on Damage Recovery and Band Gap Narrowing in Sn-Implanted β-Ga_2O_3*, Kishor Upadhyaya,* KAUST, Saudi Arabia*; D.M. Esteves, Marco Peres, Katharina Lorenz,* Instituto Superior Técnico, Portugal*; Iman Roqan,* KAUST, Saudi Arabia

We report a study on the effect of the ion charge state (Sn^+ and Sn^{++}) and the implantation dosage on the structural damage recovery and optical absorption properties of β-Ga_2O_3 thin films grown using PLD. The high

resolution x-ray diffraction (HRXRD) curves reveal that the FWHM of the implanted films are restored indicating good damage recovery while displaying transition from compressive strain into tensile strain as the implantation dosage increases. Atomic force microscopy (AFM) analysis reveals the reduction in the surface roughness value from 15.86 nm to 9.01 nm as the dosage increases indicating that the crystallite-merging becomes more efficient with the dosage. Raman spectroscopy shows that the peaks <300 cm^{-1} representing translational motions of Ga-chain disappear in higher dosage and Sn^{++} implanted films. The optical band gap shown by Tauc narrows from 4.22 eV in undoped film to 3.99 eV in Sn^{+}:1×10^{15} cm^{-2} implanted film due to shallow donor levels with band tail of implanted films extending deeper into the band gap suggesting formation of deeper states due to implantation. High resolution transmission electron microscope (HR-TEM) and differential phase contrast (DPC) mapping show that undoped films contain elongated crystallite domains throughout the film while the implanted films contain smaller crystallite domains with large number of grain boundaries extending up to 150 nm deep from the surface. These findings provide crucial insights in understanding the band gap modification and structural variations due to implantation which are important since they affect the optoelectronic properties of the film and in turn the device performances

IWGO-MoP-12 Electrical Stability of Cr_2O_3/β-Ga_2O_3 Heterojunction Diodes (HJDs) with Orientation-Dependent Breakdown Electric Field, ***Yizheng Liu,*** *Haochen Wang, Carl Peterson, Chinmoy Saha, James Speck, Chris Van de Walle, Sriram Krishnamoorthy,* University of California at Santa Barbara

This work reports the superior electrical stability of Cr_2O_3/β-Ga_2O_3 heterojunction diodes (HJDs) compared with co-fabricated NiO_x/β-Ga_2O_3 HJDs and explores the orientation-dependent breakdown electric field ($E_{Br,||}$) of Cr_2O_3/β-Ga_2O_3 HJDs fabricated on five commercially available β-Ga_2O_3 orientations. The HJDs are fabricated on highly doped n-type bulk substrates and exhibit breakdown electric field anisotropy across various orientations with the highest $E_{Br,||}$ value obtained at 12.9 MV/cm on (110) β-Ga_2O_3. Type-II band alignment between Cr_2O_3 and β-Ga_2O_3 is also reported by first-principles calculations.

The Cr_2O_3/(001) HVPE β-Ga_2O_3 HJD fabrication begins with a backside Ti/Au (50/150 nm) Ohmic metallization on n^+ β-Ga_2O_3 bulk substrate using e-beam evaporation followed by a 60-seconds rapid thermal annealing (RTA) at 470 °C in N_2. A p^- and p^{++} Cr_2O_3 stack is reactively sputtered on HVPE β-Ga_2O_3 drift region with a pre-patterned photoresist liftoff mask by optical lithography. Following the Cr_2O_3 deposition, a Ni/Au/Ni (50/50/150 nm) anode cap/metal hard mask stack is deposited via e-beam evaporation. The fabricated HJDs are later dry-etched ~2 µm into the β-Ga_2O_3 drift region below the heterojunction interface using inductively coupled plasma (ICP) for edge termination. Similar fabrication process is also applied to NiO_x/(001) HVPE β-Ga_2O_3 HJDs for stability comparison and Cr_2O_3/n^+ β-Ga_2O_3 HJDs for breakdown electric field analysis.

The as-fabricated Cr_2O_3/β-Ga_2O_3 HJDs exhibit similar electrical characteristics compared to NiO_x-based HJDs in terms of forward current density (~125 A/cm^2 at 5 V), differential specific on-resistance ($R_{on,sp}$~12 mΩ•cm^2), and breakdown voltages (~2 kV) on 7.48-µm thick drift region with 9.45×10^{15} cm^{-3} apparent charge density. The NiO_x/β-Ga_2O_3 HJDs show significant forward current density degradation (<1 A/cm^2 at 5 V) after 10-days of ambient exposure while that of Cr_2O_3/β-Ga_2O_3 HJDs remains relatively constant. It is qualitatively determined that the sheet resistance (R_{sh}) degradation of sputtered NiO_x causes forward current density reduction in the ambient conditions, and water (H_2O) vapor in the ambient air is the main agent that increases the sheet resistance of NiO_x thin film from reactive sputtering. Cr_2O_3/β-Ga_2O_3 HJDs fabricated on n^+ β-Ga_2O_3 bulk substrates reveal $E_{Br,||}$ anisotropy across five orientations of β-Ga_2O_3 with (110) orientation exhibiting the highest breakdown electric field value at 12.9 MV/cm. Relative permittivity values used for $E_{Br,||}$ values extraction are found using first-principles calculations.

IWGO-MoP-14 NiO/Ga_2O3 Heterojunction Rectifiers with Reverse Breakdown Voltage > 8.1 kV, *Hsiao-Hsuan Wan, Jian-Sian Li, Chao-Ching Chiang,* ***Katharina Loske,*** *Travis Anderson,* University of Florida*; Aman Haque,* The Pennsylvania State University*; Marko Tadjer,* Naval Research Laboratory, USA*; Jacob Leach, Caroline Reilly,* Kyma Technologies*; Fan Ren,* University of Florida

Vertical Ga_2O_3 heterojunction diodes (HJDs) were fabricated and systematically studied to evaluate the impact of lateral contact geometry on forward and reverse device performance. The devices were formed on 32 µm thick, lightly doped (8.6×10^{15} cm^{-3}) β-Ga_2O_3 drift layers grown by halide vapor phase epitaxy on heavily doped n^+ substrates. A NiO/Ni/Au heterojunction anode was employed together with dielectric edge termination using an 80 nm SiO_2 / 45 nm SiN field-plate structure. Three device designs with different field plate dimensions (D = 10, 20, and 30 µm) between the first- and second-layer contact metals were investigated. Capacitance–voltage measurements confirmed uniform drift-layer doping, while forward I–V characteristics showed comparable saturation currents and turn-on voltages for all designs. Increasing D resulted in a reduction in on-resistance and a significant suppression of reverse leakage current at low to moderate reverse bias. The optimized device with D = 30 µm exhibited the highest breakdown voltage of approximately 8.1 kV, compared with 5.5 kV and 4.5 kV for D = 20 µm and D = 10 µm, respectively. These results demonstrate that lateral contact spacing is a critical design parameter for electric-field management and breakdown enhancement in Ga_2O_3 heterojunction diodes.

IWGO-MoP-16 Multi-Kilovolt Vertical Nio/Ga_2O_3 P-N Heterojunction Diodes with Ring-Assisted Junction Termination Extension, ***Kanghee Shin,*** Sejong University, Republic of Korea*; Ho Jung Jeon,* Seoul National University, Republic of Korea*; Jang Hyeok Park, Madani Labed, You Seung Rim,* Sejong University, Republic of Korea

To achieve high breakdown voltage (V_{BR}) of Ga_2O_3 power devices, edge termination (ET) is essential because of electric field (*E*-field) crowding at the main junction edge, which results in premature breakdown [1]. Among various ET technologies, junction termination extension (JTE) is widely used in commercial power devices due to its simple formation by single-step p-type ion implantation or diffusion. However, selective p-type doping in Ga_2O_3 remains significantly challenging [2]. To this end, Ga_2O_3 power devices commonly rely on a sputtered p-type nickel oxide (NiO) as an alternative material for JTE formation. Notably, NiO has a wide bandgap of ~3.8 eV and tunable conductivity [3]. Nevertheless, NiO single-zone JTE (SZ-JTE) exhibits large variations since its effective JTE dose depends on both doping concentration (N_{JTE}) and thickness (t_{JTE}). As a result, small deviations in both NJTE and tJTE can degrade JTE's blocking capability, resulting in a narrow process window and premature breakdown [4]. Here, we proposed a ring-assisted JTE (RA-JTE) for vertical NiO/Ga_2O_3 p-n heterojunction diodes (HJDs). The RA-JTE consists of a sputtered NiO JTE layer augmented with multiple NiO floating field rings. In addition, the multiple p^+-NiO rings are designed with their spacing gradually increasing away from the main junction. Owing to this design, RA-JTE can suppress peak E-field at the main junction edge and promote a more uniform *E*-field distribution, resulting in a V_{BR} exceeding 3 kV. TCAD simulations further indicate that RA-JTE preserves a more uniform *E*-field profile under JTE dose deviations, offering improved robustness compared with SZ-JTE. These results suggest that RA-JTE is a promising ET method for Ga_2O_3 power devices with enhanced process tolerance.

[1] H. Gong *et al.*, IEEE Electron Device Lett. **45**, 1421(2024).

[2]S. J. Pearton *et al.*, Appl.Phys. Rev. **12**, 031336 (2025).

[3] Y. Ma *et al.*, Adv. Elect. Mater. **11**, 230062 (2025).

[4] W. Sung *et al.*, IEEE Electron Device Lett. **37**, 1609(2016).

+Author for correspondence: youseung@sejong.ac.kr

IWGO-MoP-18 MOCVD-grown 12µm Thick Sn Doped (001) β-Ga_2O_3 Layers with Extremely Low Free Charge Concentrations, ***Akash Patnaik,*** UVSQ – CNRS, France*; Corinne Sartel,* UVSQ – CNRS, France*; Yunlin Zheng,* INSP, Sorbonne Université, France*; Thomas Ribault, Yves Dumont, Ekaterine Chikoidze,* UVSQ – CNRS, France

The ever-increasing demand in energy necessitates efficient power converters, with high power handling capability. *β*-Ga_2O_3 based diodes are promising devices for the next generation high voltage power-switching applications, owing to large bandgap of Ga_2O_3. To attain large blocking voltage, the *β*-Ga_2O_3 drift layer of vertical diodes should be thick(>10µm) with around $10^{16}cm^{-3}$ free carriers. There are several reports of thick unintentionally doped or low Si doped *β*-Ga_2O_3 layer with nearly $10^{16}cm^{-3}$ carrier concentration for PiN or SBD diode applications. Majority of those films were grown using HVPE growth technique . Interestingly, up to our knowledge there has been no report of thick (>10µm) *β*-Ga_2O_3 epilayers doped with Sn(tin)having less than $10^{16}cm^{-3}$free carrier concentrations, grown using MOCVD. The challenges, in having low Sn doped *β*-Ga_2O_3 and eventually low carriers, stems from "wrong" site occupancy of Sn in crystal lattice or compensating defect formation, resulting in resistive films . In this work, we report 12µm thick homoepitaxial *β*-Ga_2O_3 film with $6\times10^{16}cm^{-3}$ Sn dopants (SIMS) on Sn-doped *β*-Ga_2O_3 (001) substrate grown in a RF-heated

horizontal MOCVD reactor (MR Semicon). Growth temperature was T=875^{0}C with TMGa and TESn as Gallium and Sn precursor, respectively. The rocking curves comparison for (002) reflection of our epilayers, with (002) reflection of commercially available Sn-doped β-Ga_2O_3 substrate from NCT, Japan is performed. The full-widths at half maximum (FWHMs) of our epilayer (0.020^0) is comparable to the commercially available substrate (0.026^0), suggesting it's high structural quality. Capacitance-Voltage measurement is performed on the grown sample, using Hg-probe. The extracted charge concentration (N_d-N_a) from the CV plot, in the frequency range of 0.1MHz to 1MHz, is calculated to be around $6\times10^{15}cm^{-3}$. Thus, up to our knowledge, we demonstrate for the first time, 12µm thick MOCVD grown Sn:β-Ga_2O_3 epilayers, with very low charge concentration $n<10^{16}cm^{-3}$, necessary for high power PiN diode fabrication.

IWGO-MoP-19 Structural Properties of Mist CVD Grown Rutile GeO_2 Thin Films on TiO_2 Substrates, ***Kazuki Shimazoe***, *Shota Ishiyama,* Nagoya Institute of Technology, Japan*; Hiroyuki Nishinaka,* Kyoto Institute of Technology, Japan*; Masashi Kato,* Nagoya Institute of Technology, Japan

Rutile-structured germanium dioxide (r-GeO_2) has attracted considerable attention as a high-power switching device material owing to its high breakdown field (7.0 MV/cm), capability for ambipolar doping, and feasibility of bulk crystal growth using flux-based techniques [1]. However, these substrates are not commercially available yet; therefore, heterogeneous substrates, such as TiO_2 and sapphire, have been utilized to grow r-GeO_2. Lattice mismatches between r-GeO_2 and these heterogeneous substrates can induce phase separation with amorphous and α-quartz phases [2]. This study investigated the insertion of buffer layers to reduce lattice mismatch. Rutile structured $Ge_xSn_{1-x}O_2$, which has compositions that can be lattice-matched to both r-GeO_2 and TiO_2, was employed as a buffer layer. The $Ge_xSn_{1-x}O_2$ buffer layer consisted of six layers, each with a Ge composition from 70% to 95% in increments of 5%, gradually reducing the lattice mismatch.

GeO_2 and graded $Ge_xSn_{1-x}O_2$ buffer layers were grown by mist chemical vapor deposition (CVD). Figure 1 shows scanning electron microscopy (SEM) images and the inverse pole figure (IPF) map obtained from electron backscatter diffraction (EBSD) analysis of GeO_2 thin films on a (001) TiO_2 substrate with and without a graded buffer layer. In addition to rutile phase, α-quartz phase was detected on bare TiO_2 substrates, as shown in Figure 1 (a)-(c). The IPF map of the rutile phase is predominantly red (Figure 1 (b)), corresponding to the (001) plane, which is consistent with the substrate orientation and suggests epitaxial growth. In contrast, the IPF map in Figure 1 (c) exhibits color gradation, suggesting polycrystalline growth of α-quartz phase. As shown in Figure 1 (e), only signals attributed to (001) oriented rutile phase were observed, indicating that single-phase r-GeO_2 growth was achieved by a graded $Ge_xSn_{1-x}O_2$ buffer layer. These results revealed that reducing the lattice mismatch is effective for the growth of single-phase r-GeO_2 thin films on TiO_2 substrates.

[1] K. Bushick, et al., Appl. Phys. Lett. **117**, 182104 (2020)

[2] I. Rahaman, et al., ACS Appl. Electron. Mater. **7**, 2848–2854(2025)

IWGO-MoP-20 Epitaxy of b-$(AlxGa1-x)_2O_3$ on (001) b-Ga_2O_3 Substrates by MOCVD, ***Indraneel Sanyal,*** AIXTRON Ltd., UK*; Dan Lamb, Ciaran Llewelyn, Shreyasi Maitra, Saptarsi Ghosh,* Swansea University, UK*; Andrew Pakes, K.B.K Teo,* AIXTRON Ltd., UK

β-$(Al_xGa_{1-x})_2O_3$ has emerged as a highly promising ultra–wide–bandgap semiconductor for multi–kV power electronics. Key challenges—including particle formation, parasitic gas–phase reactions, and controllable Al incorporation—are typically addressed by tuning conventional MOCVD parameters such as VI/III ratio, reactor pressure, and growth temperature. We identify the precursor reaction zone path length, before impingement on the substrate, as an independent and selective process variable. This geometric parameter modulates the residence time without significantly affecting surface–directed mass transport or surface reaction kinetics, because the concentration boundary layer thickness remains unchanged.

We tested this hypothesis in an AIXTRON CCS 3 × 2" MOCVD reactor. Two gas–phase Al fractions—22% TMAl/(TMAl+TMGa) for samples A and B, and 52% for samples C and D were combined with two showerhead–substrate gaps: 6 mm (A, C) and 15 mm (B, D). This matrix was designed to isolate whether precursor reaction zone path length meaningfully affects Al incorporation and particle formation.

XRD measurements show the dominant β–Ga_2O_3 (002) substrate peak near 31.7°, accompanied by a lower–angle feature near 30.4° consistent with the rotated–domain (–401) reflection previously reported for MOCVD growth on (001) β–Ga_2O_3 substrates. Notably, the β–$(Al_xGa_{1-x})_2O_3$ layers exhibit a strong rotated–domain contribution as well, while a distinct alloy (002) peak at ~32.3–32.4° is much weaker to be clearly resolved. This absence is attributed to the requirement for coherently strained films and the potential complications of alloy inhomogeneity or Al segregation. Therefore, Al incorporation can be more reliably estimated from the separation $\Delta(2\theta)_{(\bar{4}01)}$. Using this approach, we estimate solid–phase Al fractions of ~22% (A), ~12% (B), ~42% (C), and ~35% (D). These results show that, at fixed TMGa, TMAl flows, reducing the gap consistently increases incorporated Al while simultaneously suppressing particle formation, as confirmed by optical microscopy.

Quantitative transport modelling incorporating the actual reactor geometry shows that the mean residence time in the parasitic reaction zone (T > 250 °C) increases from 5.1 ms at 6 mm gap to 12.8 ms at 15 mm gap—providing 2.5× more time for deleterious TMAl + O_2 oxidation reactions, which preferentially deplete TMAl relative to TMGa. Importantly, concentration boundary layer calculations show that δc remains constant—approximately 1.19 mm for TMAl and 0.94 mm for TMGa—across both gap settings. This confirms that surface–directed mass transport and reaction kinetics are not affected by the gap variation.

IWGO-MoP-21 Performance Enhancement of β-Ga_2O_3 Deep-Ultraviolet Photodetectors via Al_2O_3 Passivation, ***Hee Won Shin***, *Jang Hyeok Park, You Seung Rim,* Sejong University, Republic of Korea*; Si-Young Bae,* Pukyong National University, Republic of Korea

Deep-ultraviolet (DUV) photodetectors have attracted considerable attention for applications such as flame detection, space exploration, and sterilization monitoring [1]. Among various materials, β-Ga_2O_3 is a promising candidate for solar-blind photodetectors owing to its ultrawide bandgap (~4.8 eV), which enables selective absorption in the solar-blind region [2].

In this work, β-Ga_2O_3-based DUV photodetectors were fabricated using epitaxial thin films grown by mist chemical vapor deposition (Mist-CVD) [3]. The Mist-CVD technique offers several advantages, including a simple non-vacuum process, cost-effectiveness, and the ability to grow high-quality epitaxial films.

The effects of atomic layer deposition (ALD)-deposited Al_2O_3 passivation on the electrical and photoresponse characteristics of the devices were systematically investigated. Prior to passivation, the devices exhibited shifted and asymmetric I–V characteristics due to surface defects and trap states. After applying the Al_2O_3 passivation layer, the I–V curves shifted toward the origin and became more symmetric, indicating effective suppression of surface trap states.

Furthermore, the I–T characteristics also showed a noticeable improvement. Before passivation, the devices showed a triangular-shaped response with a pronounced persistent photoconductivity (PPC) effect [4]. In contrast, after Al_2O_3 passivation, the I–T curves exhibited a square-shaped response with fast rise and decay times, indicating effective suppression of the PPC effect.

The device performance was significantly enhanced following passivation, with responsivity increasing from 2.67×10^{-2} A/W to 2.20 A/W – an improvement of approximately two orders of magnitude. Simultaneously, the on/off ratio rose from 3.63×10^2 to 6.84×10^4 due to the simultaneous reduction in dark current and increase in photocurrent.

These results demonstrate that Al_2O_3 passivation effectively suppresses surface trap states and significantly enhances the electrical stability and photoresponse performance of β-Ga_2O_3-based DUV photodetectors.

[1] C. Avila-Vendano, J. A. Carvajal-Fresno, and M. A. Quevedo-Lopez, IEEE Sensors J. 21, 14815 (2021)

[2] Z. Galazka, Semicond. Sci. Technol. 33, 113001 (2018)

[3] K. Uno, M. Ohta, and I. Tanaka, Appl. Phys. Lett. 117, 052106 (2020)

[4] S. Hullavarad, N. Hullavarad, D. C. Look, and B. Claflin, Nanoscale Res. Lett. 4, 1421–1427 (2009)

+Author for correspondence: youseung@sejong.ac.kr

IWGO-MoP-22 Suppression of Twin Nucleation in Bulk β-Ga_2O_3 Using Wide-Width Seeds, *Won-Jae LEE,* Dong-Eui University, Republic of Korea*;* ***Eun-Seo LEE***, Dong Eui University, Republic of Korea*; Eun-Jeong An, Sang-Jin Bae, Ho-Gyun Yun, Jung-Gon Kim, Kwang-Hee Jung, Mi-Seon Park,* Dong-Eui University, Republic of Korea*; Dong-Jin Lee, Jin-Ki Kang,* AXEL, Republic of Korea

In the growth of bulk β-Ga_2O_3 crystals by the edge-defined film-fed growth (EFG) method, twin defects frequently arise during the shouldering stage.

This phenomenon is initiated when the degree of supercooling at the growth interface reaches the energy threshold required for twin nucleation as the expanding crystal diameter perturbs thermal stability. The resulting twin defects disrupt the structural integrity of the crystal and significantly degrade the efficiency of the devices [1].

In this study, we propose an optimized growth process using a wide-width seed that corresponds to the die width, thereby fundamentally suppressing twin formation by bypassing the diameter expansion stage. Initially, a (-101)-oriented β-Ga_2O_3 ingot was grown using a conventional seed (Figure 1(a)); although it appeared to be a single crystal to the naked eye, polarized microscopy (Figure 1(b)) and HRXRD θ-2θ scans (Figure 1(c)) revealed distinct twin boundaries and crystallographic non-uniformity within the same ingot.

To resolve this issue, a wide-width seed fabricated by the vertical Bridgman (VB) method was introduced (Figure 1(d)). Since the seed width matches the die, it facilitates immediate vertical growth, enhancing interface stability and effectively eliminating the conditions for twin nucleation. Consequently, a twin-free single-crystalline β-Ga_2O_3 ingot was successfully grown (Figure 1(e)), and microscopy after polishing (Figure 1(f)) confirmed that twin defects were completely suppressed, resulting in a high-quality crystalline state.

IWGO-MoP-23 Comparison of NiO/β-Ga_2O_3 Heterojunction Diodes Fabricated Using Planar and Confocal RF Magnetron Sputtering Systems, ***Wojciech Hendzelek,*** Łukasiewicz Research Network-Institute of Microelectronics and Photonics, Warsaw University of Technology- Institute of Microelectronics and Optoelectronics,, Poland*; Aleksandra Wójcicka,* Łukasiewicz Research Network-Institute of Microelectronics and Photonics, Warsaw University of Technology- Institute of Microelectronics and Optoelectronics, Poland*; Aneta Gołębiowska,* Łukasiewicz Research Network-Institute of Microelectronics and Photonics, Poland*; Jarosław Tarenko, Oskar Sadowski, Maciej Kamiński,* Łukasiewicz Research Network-Institute of Microelectronics and Photonics, Warsaw University of Technology - Institute of Microelectronics and Optoelectronics, Poland*; Marcin Guza, Marek Wzorek,* Łukasiewicz Research Network-Institute of Microelectronics and Photonics, Poland*; Justyna Wierzbicka,* Łukasiewicz Research Network-Institute of Microelectronics and Photonics, Warsaw University of Technology - Institute of Microelectronics and Optoelectronics, Poland*; Krzysztof Czuba, Anna Szerling, Andrzej Taube,* Łukasiewicz Research Network-Institute of Microelectronics and Photonics, Poland

Application of p-type conductive oxides, such as nickel oxide (NiO) allows to produce high quality, high voltage, and low leakage current gallium oxide (β-Ga_2O_3) power diodes. NiO active layers are often deposited using reactive magnetron sputtering method, and process parameters can affect both material and resulting power devices properties. However, there is a lack of direct comparison of different magnetron sputtering configurations for deposition of p-type NiO layers for β-Ga_2O_3 devices. Here, in this work, properties of vertical NiO/β-Ga_2O_3 heterojunction diodes (HJDs) obtained by confocal and planar sputtering magnetron system were compared. The devices were fabricated on n^+-β-Ga_2O_3 epi layers (N_D~$6.5x10^{15}cm^{-3}$) grown by HVPE on bulk (001) β-Ga_2O_3 substrates. The NiO/Ni/Au anodes were fabricated using lift-off photolithography and deposition of 100 nm NiO layers by means of RF magnetron sputtering using ceramic NiO target. Nickel oxide layers were deposited with different oxygen contents in the Ar/O_2 gas mixture equal to 0, 10, 20, 30% in both planar down pO_2 (oxygen partial pressure) and confocal down fO_2 (oxygen partial flow) sputtering magnetron systems.Diodes with a NiO layer deposited in pure Ar atmosphere were characterized by Schottky-like or double-barrier I-V characteristics. Devices with a NiO layer from a confocal magnetron sputtering possess a lower ideality factor (n = 1.02), higher forward current over 200 A/cm^2 and breakdown voltage over 1600V as compared to diodes produced with a NiO layer obtained from a planar system. However, it shows “double-barrier” like forward characteristics. Higher breakdown voltage can be associated with higher energy bandgap (E_g=3.71 eV) as well as higher resistivity of layers deposited using confocal sputtering system. Devices with NiO layer deposited in a reactive atmosphere (pO_2 = fO_2 = 10-30%) were characterized by a typical p-n heterojunction characteristics with higher turn-on voltages. Higher forward current and breakdown voltage were observed for HJDs fabricated means of confocal magnetron sputtering system as compared to planar one. Ideality factors as low as n~1,15 were obtained for all diodes, regardless of oxygen partial flow. This work has been partially supported by the Wide Bandgap (WBG) Pilot line, which is funded jointly by the Chips Joint Undertaking, through the European Union’s Digital Europe programme and Horizon Europe programme, as well as by the participating states Italy, Sweden, Poland, Finland, Austria, France and Germany, under Grant Agreement n. 101183211

IWGO-MoP-25 Engineering Considerations for the Growth of Sb-Doped Sn0.4Ge0.6O2 Thin Films, ***Avery-Ryan Ansbro****, Yi Liang, Pat Kezer, Manasi Londhe, John Heron,* University of Michigan, Ann Arbor

Rutile germanium dioxide (r-GeO_2) has drawn a lot of attention due to its large bandgap, structural stability, and high thermal conductivity. Enhanced stability offered through alloying with SnO_2 makes these rutile structured oxides excellent candidates for next generation power electronic devices. Due to rutile oxides only recently being recognized as ultra-wide bandgap semiconducting materials, potential dopant and contact materials remain speculative.

In this work, we confirm Sb as an effective dopant in single crystal r-$Sn_{0.4}Ge_{0.6}O_2$ thin films grown on (10-10)-oriented sapphire substrates. Through variation of doping concentrations from 0.03-3.3%, we identify lower and upper doping limits for thin films. Additionally, we can achieve carrier densities up to 1.7 x 10^{20} cm^{-3} and mobilities up to 33 cm2/Vs at room temperature. Challengingly, it is observed that under oxygen rich annealing conditions, germanium vacancies can act as electron sinks, drastically reducing carrier mobilities and rendering films insulating. We confirm that Sb can still behave as an effective donor so long as annealing occurs under reduced oxygen environments. Our work establishes optimized conditions for synthesizing Sb-doped thin films using pulsed laser deposition and the interplay between electron transport and deposition conditions.

IWGO-MoP-28 Lock-in Infrared Thermography Techniques for Thermal Characterization of Ultra-Wide Bandgap Semiconductors, ***Ethan Scott****, Jessica Reyes,* University of Virginia*; Jeffrey Braun, John Gaskins,* Laser Thermal*; Marko Tadjer,* Navel Research Laboratory*; Patrick Hopkins,* University of Virginia

Ultra-Wide Bandgap (UWBG) semiconductors offer excellent performance for high-power applications. Their physical properties enable high critical breakdown fields, and their strong atomic bonds make them inherently stable at elevated temperatures. However, despite this potential, the performance of UWBG devices is still limited by material quality, defect density, and doping challenges, which also directly affect thermal performance. For materials such as gallium oxide, which naturally exhibit low thermal conductivity, any further reduction poses a significant engineering challenge. Therefore, accurate assessment of thermal performance is critical.Thermoreflectance techniques are among the most prevalent methods for measuring the thermal conductivity of UWBG substrates and films, offering excellent spatial resolution. However, they often require a mirror-like surface and a thin metal optothermal transducer. For example, as-deposited films can have a surface roughness incompatible with thermoreflectance, which necessitates sample polishing or membrane fabrication. In cases where samples have a thickness-dependent structure (e.g., a nucleation layer), polishing the top surface can affect the apparent measured thermal conductivity.Lock-in infrared thermography (LIT) provides an alternative approach, using a similar analysis to thermoreflectance while not strictly requiring a transducer layer and being insensitive to surface roughness. In this talk, we detail the advantages and limitations of LIT, demonstrating that it is well-suited for measurements of high-thermal-conductivity substrates and offers potential for higher measurement throughput.

IWGO-MoP-29 Reverse Leakage Reduction of *β*-Ga_2O_3 Schottky Barrier Diode by *Ex-Situ* Mg Annealing Diffusion, ***Zhiyu Xu****, Jia Wang, Haitao Wang, Hiroshi Amano,* Nagoya University, Japan

This work studies the leakage current characteristics of Ga_2O_3 Schottky barrier diodes (SBDs) employing metallic magnesium (Mg) as an *ex-situ* diffusion source for Schottky barrier engineering. The epitaxial structure consists of a 5 μm unintentionally doped (UID) *β*-Ga_2O_3 layer (n ≈ $2.6×10^{16}$ cm^{-3}) grown by hydride vapor-phase epitaxy (HVPE) on a (001)-oriented n-type Sn-doped *β*-Ga_2O_3 substrate (NCT). A 10 nm thick Mg layer was deposited by sputtering on patterned regions, followed by liftoff. The Mg diffusion process was performed by thermal annealing at various temperatures in O_2 or N_2 ambient for different durations. The wafers were then cleaned by acid to remove Mg residue and other amorphous compound formed during annealing. Ni/Au Schottky contact was deposited on the Mg-treated mesa regions by e-beam evaporation, and an Al backside contact was subsequently deposited by sputtering. No edge termination or passivation was applied in these SBDs. A reference sample without Mg annealing process was also fabricated.

The forward and reverse *J-V* measurement results for 200µm diameter SBD are shown in Fig. 1. Under forward bias, almost all SBDs have the same behavior as the reference device except that annealing at 800°C shows an increased turn-on voltage. Compared to the annealing in N_2 ambient, the annealing process of Ga_2O_3 in O_2 ambient better suppresses the reverse leakage current with stable device performance. It was found that with thin Mg deposition thickness of 10nm, the mild annealing temperature of 600-650°C shows lower leakage current compared to annealing at higher temperature of 800°C. Furthermore, extending the annealing time from 5 minutes to 10 minutes at 650°C increases the reverse leakage, indicating that Mg diffusion needs to be controlled such that there exists a window for moderate Mg diffusion concentration for the optimized reverse leakage characteristics of Mg-annealed β-Ga_2O_3 SBD.

IWGO-MoP-30 In-situ Reflectometry for Monitoring Growth Rate, Surface Morphology, and Doping in MOVPE Homoepitaxy of β-Ga_2O_3, ***Kolja Haberland***, LayTec AG, Germany; *Ta-Shun Chou,* NextGO Epi UG, Germany; *Andreas Fiedler, Adreas Popp, Saud Bin Anooz, Raimund Grüneberg, Jana Rehm, Arub Akhtar,* Institut für Kristallzüchtung IKZ, Germany

The MOVPE growth of gallium oxide remains challenging, as precise control of layer thickness, surface morphology, and doping levels is required to produce device-grade epitaxial wafers for lateral and vertical transistors and to enable scaling to larger wafer sizes. In-situ optical metrology methods such as pyrometry and reflectometry therefore play an important role in understanding and controlling the growth process [1]. For fundamental studies, gallium oxide layers can be grown heteroepitaxially on sapphire substrates. Due to the refractive index contrast between the film and the substrate, strong Fabry–Pérot oscillations appear in the reflectance signal, enabling straightforward determination of growth rate and layer thickness. However, transistor applications require growth on native gallium oxide substrates, resulting in homoepitaxy where the refractive index contrast is minimal and Fabry–Pérot oscillations are largely suppressed.

In this work, we demonstrate that in-situ reflectometry can nevertheless provide critical growth information during homoepitaxial growth. Small variations in refractive index enable extraction of growth rate and layer thickness using an autocorrelation-based analysis of the reflectance signal. In addition, short-wavelength reflectometry at 280 nm provides a sensitive method for real-time monitoring of surface roughness during growth, independent of the substrate material. Furthermore, we present results on the determination of doping levels in Si-doped gallium oxide using in-situ reflectometry. Significant refractive index changes with doping level are observed and attributed to plasmonic effects described by the Drude approximation. This enables correlation of doping levels with the in-situ reflectance signal, demonstrating the potential of optical in-situ metrology for real-time monitoring of doping during MOVPE growth.

With such in-situ monitoring, independent of the substrate and even the MOVPE tool, the growth can be precisely monitored.

[1] Journal of Crystal Growth 603 (2023) 127003

Author for correspondence: kolja.haberland@laytec.de

IWGO-MoP-31 Epitaxial β–$(Al_xGa_{1-x})_2O_3$ Thin Films Grown on (100) β-Ga_2O_3 by MOVPE, ***Deborah Kern***, *Martin Handwerg, Ta-Shun Chou, Saud Bin Anooz, Martin Schmidbauer, Andreas Popp, Andreas Fiedler,* Leibniz Institute for Crystal Growth, Germany

One major drawback of Ga_2O_3 is its low electron mobility. To overcome this limitation in homoepitaxial β-Ga_2O_3, a modulation-doped β-$(Al_xGa_{1-x})_2O_3$/Ga_2O_3 heterostructure has been proposed to induce a high-mobility two-dimensional electron gas (2DEG) at the interface, which can be used in high electron mobility transistors (HEMT). However, a comprehensive understanding of the growth mechanisms, as welle as the surface and reaction behavior of aluminum-alloyed gallium oxide layers is still lacking.

We report on the growth of fully strained epitaxial thin layers (15-60 nm thickness) of β–$(Al_xGa_{1-x})_2O_3$ on β–(100) Ga_2O_3 with an offcut angle of 4° by metal-organic vapor phase epitaxy (MOVPE) with an Al content around 40%. With increasing the Ga flow, the growth rate increased linearly up to approximately 30 nm/min at constant Al flow (Fig. 1a). With a higher Ga flow, a smoother surface with a step-bunching morphology with less particles is observed (Fig. 1b). The Al content in the layers stayed roughly constant with increasing Ga flow, might suggesting that a Ga wetting-layer is formed. The Ga wetting layer influences adatom diffusion, allowing Al adatoms to migrate over the Ga-rich surface and incorporate into the crystal lattice, effectively “sinking” from the adlayer to form a thin layer. Thus, Ga acts as a surfactant for the growth of β-$(Al_xGa_{1-x})_2O_3$, possibly attributed to a metal-exchange catalysis mechanism similar to the reported In-catalyzed Ga_2O_3 growth via MBE.[1]

This work is an important step toward understanding the growth of Al-alloyed heterostructures for achieving high-efficiencyHEMT devices.

[1] P. Vogt, O. Brandt, H. Riechert, J. Lähnemann, O. Bierwagen, PRL **119**, 196001 (2017).

IWGO-MoP-32 NiO/β-Ga_2O_3 Vertical Pin Diodes with Low Leakage and Size Dependent Transport Characteristics, ***Tom Micottis,*** Institute of Electronics, Microelectronics and Nanotechnology (IEMN), France

β-Ga_2O_3 has emerged as a promising ultra-wide bandgap semiconductor for high-voltage power electronics due to its large bandgap (~4.8 eV) and high critical electric field. However, the absence of reliable p-type doping remains a key limitation for the realization of bipolar devices. One approach to overcome this challenge consists of using p-type oxides to form heterojunction PiN structures with n-type Ga_2O_3.

In this work, vertical $Ni_{1-x}O$/β-Ga_2O_3 PiN diodes were fabricated on Si-doped β-Ga_2O_3 substrates with a 10-µm-thick n^- Ga_2O_3 drift layer ($N_D \approx 10^{16}$ cm^{-3}). The $Ni_{1-x}O$ layer used to form the heterojunction was optimized in a companion study focusing on the electrical properties of p-type $Ni_{1-x}O$ thin films. A 3 µm-deep mesa structure was implemented to mitigate electric field crowding at the device periphery and improve the overall electrical performance.

Electrical characterization was performed on devices with anode diameters ranging from 80 µm to 450 µm. Forward measurements show rectifying behavior with a turn-on voltage of approximately 1.9 V. The forward current density increases with the device diameter, while smaller diodes exhibit reduced current density. This size dependence suggests that forward transport is not purely limited by bulk series resistance but is influenced by perimeter-related effects and non-uniform carrier injection at the $Ni_{1-x}O$/β-Ga_2O_3 heterojunction.

Reverse measurements reveal low leakage current densities in the 10^{-7}–10^{-8} A/cm^2 range and a diameter-dependent breakdown behavior, where larger devices exhibit earlier breakdown, likely due to electric-field crowding at the device periphery, combined with increased sensitivity to local defects in larger-area devices.

Temperature-dependent measurements further reveal a transition from injection-limited transport in small devices to drift-limited conduction in larger diodes. While larger diodes exhibit a decrease of forward current with increasing temperature, consistent with mobility degradation in the Ga_2O_3 drift layer, smaller devices show a thermally activated current increase, suggesting injection-limited transport at the heterojunction.

A benchmark of leakage current density versus breakdown voltage is presented and compared with reported $Ni_{1-x}O$/β-Ga_2O_3 heterojunction diodes. These results highlight the competitive among the lowest reported leakage performance of the proposed devices and provide insights into the transport mechanisms governing the scaling of vertical Ga_2O_3 heterojunction power diodes.

IWGO-MoP-33 Electronic and Electrical Properties of $Mg_xNi_{1-x}O$ Thin Films Deposited by Rf Magnetron Sputtering, ***Harunobu Yasuda***, *Shunya Matsui, Takayuki Akiba, Tomohiro Yamaguchi, Tohru Honda,* Department of Electrical Engineering and Electronics, Graduate School of Engineering, Kogakuin University, Japan; *Hironobu Miyamoto, Kohei Sasaki,* Novel Crystal Technology, Japan; *Takeyoshi Onuma,* Department of Electrical Engineering and Electronics, Graduate School of Engineering, Kogakuin University, Japan

β-Ga_2O_3 is known as a novel material for power electronics. [1,2] We have been focusing on $Mg_xNi_{1-x}O$ alloy as a material for pn heterojunction with β-Ga_2O_3. Electric property, bandgap, and band alignment have been reported for $Mg_xNi_{1-x}O$ with x≤32%. [2,3] In this study, $Mg_xNi_{1-x}O$ films were deposited by RF magnetron sputtering for x≤0.58, and their electronic and electrical properties were evaluated.

$Mg_xNi_{1-x}O$ films were deposited by RF magnetron sputtering in an O_2 atmosphere at an ambient temperature. A NiO target and c-plane sapphire or quartz glass substrate were set with a distance of 3 cm. To alloy with MgO, the NiO target was co-sputtered with 0 to 16 pieces of 10×10 mm^2 square-shaped MgO substrates. RF power and sputtering pressure were fixed at 150 W and 0.75 Pa, respectively. Since sputtering rate decreased with increasing the number of MgO substrate, sputtering time was varied in a range 10-30 minutes to adjust film thickness in a range 106-140 nm. Resistivity was measured by the four-point probe method with van der Pauw configuration. Mg composition was quantified by energy dispersive X-ray spectrometry. Optical transmittance spectra were measured by UV-Vis

spectrophotometer. Valence band offset (ΔE_v) at the MgNiO/sapphire interface was determined by X-ray photoelectron spectroscopy.

As shown in Fig. 1, room temperature resistivity increased monotonically with increasing x. All the films were confirmed to show a p-type conductivity by Seebeck effect measurement. Absorption edge E_{edge}, which was determined by the Tauc plot, increased with x in a range 3.69-4.28 eV. The Tauc plot showed additional onset in a range 3.74-5.49 eV. The former is attributed to O 2p to Ni 3d charge transfer transition, and the latter is originated from valence to conduction band transition giving bandgap E_g. [5] ΔE_v decreased with x in a range 2.31-1.57 eV.The results may imply that breakdown voltage is expected to be higher for large x with maintaining low on-voltage.

This work was supported in part by the New Energy and Industrial Technology Development Organization (NEDO), subsidized by project No. JPNP22007. [1] M. Higashiwaki *et al*., J. Phys. D: Appl. Phys. **50**, 333002 (2017).[2] K. Sasaki, Appl. Phys. Express **17**, 090101 (2024). [3]M. Murayama *et al*., IWGO4, (2022), Pos 1-41.[4] T. Onuma *et al*., IWGO5, (2024), TuP_46. [5] T. Saitoh *et al*., Appl. Phys. Lett. **112**, 041904 (2018). [6] A. M. E. Raj *et al*., Cryst. Res. Technol. **42**, 867 (2007).

IWGO-MoP-34 Improved Structural and Electrical Properties of MOCVD-Grown β-Ga_2O_3/Sapphire Films with Compositionally-Graded ($Al_xGa_{1-x})_2O_3$ Buffer, ***Filip Gucmann***, *Sai Gurukrishna Vadlamudi, Kristína Hušeková, Edmund Dobročka, Peter Nádaždy, Dagmar Gregušová, Iryna Kozak, Ondrej Pohorelec,* Institute of Electrical Engineering, Slovak Academy of Sciences, Slovakia*; Matej Mičušík,* Polymer Institute, Slovak Academy of Sciences, Slovakia*; Igor Píš, Milan Ťapajna,* Institute of Electrical Engineering, Slovak Academy of Sciences, Slovakia

We report on β-$(Al_xGa_{1-x})_2O_3$/β-Ga_2O_3 (AlGaO/GaO) heterostructures grown on c-plane sapphire by liquid-injection MOCVD. AlGaO buffers were compositionally-graded with varying starting Al content (5, 15, 30 at. %) via novel fully-autonomous liquid precursor dosing to achieve linear gradient for mitigation of the lattice mismatch. As opposed to our previous results, Si-doped GaO films grown on AlGaO buffers exhibited improved crystallinity: GaO X-ray rocking curve showed best FWHM of ~1.6°, while only ~0.9° for AlGaO buffer with 5% Al content. However, signs of phase separation were observed for AlGaO films with 15% and 30% Al content. Significantly improved was RT electron mobility μ_e ~8 cm^2/Vs at n_e ~1.3×10^{19} cm^{-3} (ρ = 0.078 Ω·cm) compared to the films prepared directly on sapphire which showed μ_e ~0.6-1.7 cm^2/Vs and strong electron localization. Depletion-mode MOSFETs showed output current of ~9 mA/mm but did not fully pinch-off (before gate dielectric breakdown) without gate recess. Further, strong suppression of parasitic (310)-oriented crystallites, previously achieved via the use of off-cut substates, was observed for 5% Al content AlGaO buffers, while only minor content was observed in subsequently-grown GaO films. Implementing the AlGaO buffer led to several times larger GaO grains than previously; RMS surface roughness of AlGaO and GaO films were 3.8 and 11 nm, respectively. We further evaluate electronic structure, depth-resolved chemical composition, stoichiometry, and electric transport properties via photoluminescence, X-ray photoelectron spectroscopy, elastic recoil detection analysis, and low-T I-V measurements, respectively.

IWGO-MoP-35 Reduction of Si Impurities in β-Ga_2O_3 Homoepitaxial Films Grown by Mist-CVD, ***Yuki Isobe,*** Kyoto University, Japan*; Yuki Yamamoto,* OXIDE Corporation, Japan*; Hirokazu Izumi,* Hyogo Prefectural Institute of Technology, Japan*; Takeru Wakamatsu,* Kyoto University, Japan*; Kentaro Kaneko,* Ritsumeikan University, Japan*; Shizuo Fujita, Katsuhisa Tanaka,* Kyoto University, Japan

β-Ga_2O_3, one of the ultra-wide-bandgap semiconductors with a bandgap of 4.6-4.9 eV, has attracted attention because of its potential applications for power electronics. Thus far, the control of carrier concentration in the range of 5 × 10^{17} cm^{-3} to 2 × 10^{20} cm^{-3} has been achieved for thin films obtained by mist-CVD [1]. However, compared to other growth processes, the carrier concentration remains relatively high. The carrier concentration below 10^{17} cm^{-3} is required for achieving a breakdown voltage above 1 kV. This is partly because unintentional impurities such as Si are incorporated into thin films during the growth process. In this work, an attempt was made to reduce the concentration of unintentional impurities, especially, Si by inner-wall coating of silica tube used for the thin film growth and cleaning of substrate surface prior to the preparation of β-Ga_2O_3 thin films on β-Ga_2O_3 substrates.

Figure 1 shows SIMS profiles of Si in thin films and substrates before and after the cleaning of substrate surface with hydrofluoric acid and inner-wall coating of silica glass tube. It is clear that the concentration of Si was reduced by both treatment with hydrofluoric acid and inner-wall coating. Figure 2 depicts relationship between electron mobility and carrier concentration obtained by the Hall effect measurements. The carrier concentration was reduced by both hydrofluoric acid treatment and inner-wall coating. For the thin film grown in the silica glass tube the inner-wall of which was coated with both Ga_2O_3 and Al_2O_3, the carrier concentration is decreased to 6.3 × 10^{16} cm^{-3}, and the electron mobility reaches 129 $cm^2V^{-1}s^{-1}$.

This work was supported by the New Energy and Industrial Technology Development Organization (NEDO) under project JPNP21005.

[1] T. Ogawa et al., Jpn. J. Appl. Phys. 62, SF1016 (2023).

IWGO-MoP-36 Prospects of Safe and Cost-Effective Mist CVD for Homoepitaxial Growth and Devices of β-Ga_2O_3, ***Shizuo Fujita,*** *Takeru Wakamatsu, Yuki Isobe, Hikaru Ikeda,* Kyoto University, Japan*; Yuji Ando, Hidemasa Takahashi, Ryutaro Makisako,* Nagoya University, Japan*; Tetsuzo Ueda,* Panasonic, Japan*; Jun Suda, Katsuhisa Tanaka,* Kyoto University, Japan*; Hidetaka Sugaya,* Panasonic, Japan

Mist CVD has evolved as a safe and cost-effective method for growing oxide thin films such as those used for transparent conductors, passivation layers, and coating films. However, its application to the growth of device-quality semiconductor layers has hardly been investigated, as it is considered inferior to MOCVD or MBE in terms of source purity and the potential for impurity incorporation. At Kyoto University, based on the experience that β-Ga_2O_3 films grown on β-Ga_2O_3 substrates exhibit good surface morphology and crystallinity, owing to homoepitaxy, efforts have been made to reduce residual impurities in β-Ga_2O_3 films. Recently, the donor concentration became controllable in the order of $10^{17}cm^{-3}$, where the breakdown voltage could be >800 V.

To demonstrate the potential applications of mist CVD-grown β-Ga_2O_3 films in devices, we presented successful operation of MESFETs with the gate length (L_G) of 2 μm [1], followed by those with a L_G of 0.45 μm and an effective gate width (W_G) of 150 μm showing a current gain cut-off frequency (f_T) and a maximum oscillation frequency (f_{max}) of8.3 and 18.4 GHz, respectively [2]. In this presentation, we demonstrate advanced RF characteristics of MESFETs with larger $W_G$showing higher power and gain.

We used a (010)-oriented 2-inch β-Ga_2O_3 substrate grown by the vertical Bridgeman method. The substrate was divided into four pieces on which the growth was performed by mist CVD. The β-Ga_2O_3 epitaxial layer was Ge-doped and had a thickness of 61 nm. The electron concentration and mobility were estimated at 1.5x10^{18} cm^{-3} and 85 cm^2/Vs, respectively, based on the Hall effect measurements. The MESFETs were fabricated at the C-TEFs of Nagoya Universityusing stepper lithography. The L_G and W_G were 0.4 and 600 μm, respectively. An example of the DC characteristics revealed the maximum drain current and transconductance of 93 mA/mm and 33 mS/mm, respectively, at the drain voltage of 10 V. An amplifier using the MESFET showed a maximum output power of 19 dBm (80 mW), a linear gain of 10dB, and a maximum added efficiency of 15 % at 2.48 GHz by placing the matching circuit near the device. The output power was more than six times higher than that of our previous device [2] owing to the larger gate width. However, the drain current is not high enough, and overcoming this is one of our future objectives. Nevertheless, these results encourage the use of mist CVD may as a cost-effective device fabrication technology.

We acknowledge Novel Crystal Technology, Inc. for supplying a 2-inch β-Ga_2O_3 substrate.

[1] H. Takane *et al*., Appl. Phys. Express **16**, 081004 (2023); [2] H. Ikeda *et al*., Jpn. J. Appl. Phys. **64**, 108002 (2025).

IWGO-MoP-39 First-Principles and Thermodynamic Study of (AlxGa1-x)2O3 Growth by PA-MBE, ***Rie Togashi,*** Sophia University, Japan*; Akira Kusaba,* Kyushu University, Japan*; Masataka Higashiwaki,* Osaka Metropolitan University/NICT, Japan*; Yoshinao Kumagai,* Tokyo University of Agriculture and Technology, Japan

Ga_2O_3 and $(Al_xGa_{1-x})_2O_3$ alloys have attracted attention as materials for next-generation high-power devices. In this study, the composition dependence of the formation enthalpy, Δ*H*, of $(Al_xGa_{1-x})_2O_3$ alloys in the α and β phases was investigated by first-principles calculations. For simplicity, the calculated results were approximated using a regular solution model. Based on these results, thermodynamic analysis was performed for plasma-assisted molecular beam epitaxy (PA-MBE) growth of $(Al_xGa_{1-x})_2O_3$.

For β-$(Al_xGa_{1-x})_2O_3$, three Al occupation models were considered: octahedral-site occupation (β-oct), random occupation of octahedral and

tetrahedral Ga sites (β-rand), and tetrahedral-site occupation (β-tet). The results indicate that Al preferentially occupies the octahedral site. The composition-dependent formation enthalpies for α- and β-$(Al_xGa_{1-x})_2O_3$ were approximated using the regular solution model, $\Delta H = \Omega x(1-x)$. The fitted Ω values were 511 cal/mol-cation for β-oct, 3021 cal/mol-cation for β-tet, and 2108 cal/mol-cation for α-$(Al_xGa_{1-x})_2O_3$, corresponding to critical temperatures (T_c) of −145, 487, and 257 °C, respectively. The low T_c for β-oct suggests that compositional separation is unlikely within the β phase.

The relationship between the gas-phase composition ratio, $R_{Al}(=P°_{Al}/P°_{III})$, and the solid-phase Al composition x was also investigated under various oxygen input partial pressures. Under O-rich growth conditions, R_{Al} was nearly equal to x. In contrast, under metal-rich growth conditions, x shits toward Al_2O_3-rich compositions with increasing R_{Al} because the input Ga becomes Ga_2O(g) and remains in the gas phase. The calculated results agree well with the experimental data. These results indicate that, under the present PA-MBE conditions, the growth of $(Al_xGa_{1-x})_2O_3$ is thermodynamically limited.

This work was supported in part by the Collaborative Research Program of Research Institute for Applied Mechanics, Kyushu University.

[1] T. Ohtsuki, J. Vac. Sci. Technol. A **41**, 042712 (2023).

IWGO-MoP-40 Benchmarking Gate Charge in Gallium Oxide Transistors, ***Daniel Dryden***, Air Force Research Laboratory

Gate charge Q_G is a useful metric for understanding and predicting the switching speed and loss of high-voltage power switches, but is difficult or impossible to directly measure on-wafer for ultra-wide band gap devices due to their extremely low gate charges and fast switching speeds. New methods for extracting Q_G are therefore necessary in order to effectively benchmark Ga_2O_3 devices. We have explored three means of estimating gate charge: split C-V, s-parameter extraction, and geometric approximation. The geometric method provides a conservative order-of-magnitude estimate of Q_G. Q_G from split C-V measurements are in good agreement with datasheet values for COTS parts and agree within an order of magnitude with the $Q_{G,geometric}$ for lateral Ga_2O_3 devices. S-parameter extraction agrees well with split C-V data and has a lower noise floor, improving accuracy for small-periphery devices. Work is ongoing to correlate these values to transient switching measurements and to determine the best practices for accurate Q_G extraction. Overall, these methods provide a useful suite of techniques for researchers looking to benchmark switching performance for small, UWBG devices with low Q_G.

IWGO-MoP-41 Defect Characterization of Czochralski Grown Gallium Oxide, *Alecsander Imhof,* ***Nadeemullah Mahadik***, *Marko Tadjer,* Naval Research Laboratory*; Robert Lavelle,* Pennsylvania State University

The high electrical breakdown strength, ease of melt-growth, and high Baliga's figure of merit of beta-phase gallium oxide (b-Ga2O3) make it a desirable ultra-wide-bandgap semiconductor material for the fabrication of next-generation power devices [1]. b-Ga2O3's material characteristics make it a competitive with other wide-bandgap materials GaN and SiC [2,3]. Wafer quality is crucial to the future development and adoption of -devices as dislocations and other structural defects have negative impacts on their performance and reliability. Characterization of the different -production methods has already begun in an effort to understand and mitigate dislocations [4,5,6].

This work focuses on the characterization of defects in an axial slice from seed to dome of b-Ga2O3 commercially grown by SYNOPTICS using the Czochralski (CZ) method. High resolution x-ray topography (XRT) was used to observe threading dislocations that propagate throughout the slice. To obtain clear XRT images, the sample surfaces were subjected to chemical–mechanical polishing (CMP) to remove damage introduced during mechanical processing prior to XRT observation. Figure 1 shows two XRT images taken with g = 912 and g = 605. Note that the horizontal lines that appear in Fig. 1(a) do not appear in Fig. 1(b). Using contrast analysis, the invisibility criterion, the Burgers vectors of these horizontal lines must contain a component. As the growth direction for CZ grown b-Ga2O3 is these striations can be characterized as threading screw dislocations as their Burgers vector and dislocation direction are parallel. Using the data, it was calculated that the density of the TSDs on the seed side was ~1000/cm2 which dropped to ~400/cm2 on the dome side. It was observed that the TSDs either annihilated, converted to basal plane dislocations (BPDs), or combined into a single TSD. The while circular contrasts in Fig 1(a) are basal plane dislocations and their density in the slice also decreases from seed side to dome. The average density dropped from ~400/cm2 to ~100/cm2. Finally, the long dislocations in these images are threading mixed dislocations TMDs as their line direction changes as they migrate through the slice and they appear in both Fig 1(a) and 1(b) The density of the TMDs once again drops from seed side to dome side, with the averages of ~150/cm2 and ~50/cm2 respectively. Further details of the defects and their evolution will be presented.

IWGO-MoP-43 Gd Incorporation in β-Ga_2O_3 Grown by Suboxide MBE: Towards Ultraviolet Emission and Luminescent Thermometry, *Martin Samuel Williams, Marco Schowalter,* ***Alexander Karg***, *Mahmoud Elhajhasan,* University of Bremen, Germany*; Marcus Rohnke,* University of Giessen, Germany*; Carsten Ronning,* University of Jena, Germany*; Gordon Callsen, Andreas Rosenauer, Martin Eickhoff, Manuel Alonso-Orts,* University of Bremen, Germany

β-Ga_2O_3 has emerged as a promising ultra-wide bandgap semiconductor for next-generation power electronics and solar-blind photonics. Rare-earth doping offers an attractive route to introduce spectrally well-defined optical transitions. In particular, Gd^{3+} exhibits intra-4f transitions in the UV-B spectral region. The Stark manifold of Gd^{3+}, consisting of a single ground state and split excited multiplets, is largely insensitive to small crystal-field variations due to shielding of the 4f electrons by the outer 5s and 5p orbitals, while remaining responsive to larger symmetry changes such as those between Ga_2O_3 polymorphs. In addition, this manifold enables temperature-dependent population redistribution among crystal-field split levels, which can be exploited for high-precision luminescent thermometry [1].

Our recent work [2] studied Gd implantation in β-Ga_2O_3 thin films grown by atomic layer deposition (ALD) and molecular beam epitaxy (MBE). Detailed photoluminescence (PL) spectroscopy revealed a well-resolved manifold of four lines in the UV-B originating from the electronic transitions from the Stark splitting of the $^6P_7/_2$ excited state to the $^8S_7/_2$ ground level of Gd^{3+}. These results indicated that the transition energies in implanted β-Ga_2O_3:Gd films are largely independent of the growth method (for the undoped β-Ga_2O_3 films) and of the annealing conditions in the Gd-implanted layers, reflecting the weak sensitivity of the 4f electronic states to such small variations in the host crystal environment

In this work, we extend these studies to epitaxially grown Ga_2O_3:Gd layers synthesized by suboxide molecular beam epitaxy (S-MBE) [3]. Growth was performed under adsorption-controlled and oxygen-rich conditions. Structural characterization by reflection high-energy electron diffraction (RHEED) and X-ray diffraction (XRD) confirms the formation of crystalline β-Ga_2O_3 layers, while XRD and depth-resolved X-ray photoelectron spectroscopy (XPS) provide evidence for successful Gd incorporation into the films. These results demonstrate the feasibility of in-situ Gd incorporation during suboxide MBE growth and establish a platform for studying rare-earth optical properties in epitaxial Ga_2O_3, enabling direct comparison with implanted samples [2] and opening pathways towards engineered UV-B emitters and temperature-sensing photonic devices.

References

[1] D. Yu, (...), M. Suta, Light Sci. Appl. **10,** 236 (2021).

[2] M. S. Williams, (...), M. Alonso-Orts, Mater. Today Phys. **54**, 101731 (2025).

[3] P. Vogt, (...), J. S. Speck, APL Mater. **9**, 031101 (2021).

IWGO-MoP-46 Growth of NiO/ β-Ga_2O_3 Heterojunction Diodes using Plasma-Assisted Molecular Beam Epitaxy, ***Dagny Sacksteder***, Colorado School of Mines*; Anna Sacchi,* National Laboratory of the Rockies*; Megan Holtz,* Colorado School of Mines*; M. Brooks Tellekamp,* National Laboratory of the Rockies

β-Ga_2O_3 is a promising ultrawide band gap material for power electronics. While it cannot be doped p-type, NiO/β-Ga_2O_3 heterojunction diodes (HJD) are a promising alternative to realizing devices. Nevertheless, extended defects at the HJD interface formed during growth via sputtering or pulsed laser deposition can lead to field crowding and premature breakdown. Molecular beam epitaxy (MBE) growth can address this challenge, providing atomic-scale control over composition and structural quality. Here, we use MBE to explore the growth window of NiO on (100) β-Ga_2O_3. We explore various approaches to inducing extrinsic p-type conductivity in MBE-grown NiO films and establish the need for monolithic growth to achieve the highest-quality interface and electrical performance. This work informs interface and device design in future applications of NiO/ β-Ga_2O_3 HJD.

IWGO-MoP-47 Domestic Supply-Chain Development of Discrete Ga2O3 Devices for Next-Generation Power Conversion Systems*, Jesse Johnson,* Mainstream Engineering Corporation*; Luke Lyle, Robert Lavelle, Greg Pastir,* The Applied Research Laboratory at Penn State University*; Andrew Binder, Richard Floyd, Mihai Negoita, Brian Rummel, Bob Kaplar,* Sandia National Laboratories*; David Snyder, Justin Hill,* Mainstream Engineering Corporation

Mainstream Engineering was founded as a thermal controls company that has since transformed into a successful domestic manufacturer of military and commercial products based on multi-disciplinary, solutions-oriented technology development. Our portfolio includes a range of ruggedized systems- and subsystems- level power electronics products with integrated thermal controls for ground, naval, air, and space applications. Over the past decade we adopted a deliberate drive towards developing fabrication capabilities of wide bandgap (WBG) and ultrawide bandgap (UWBG) materials to offer device-level integrated solutions for high power/high temperature opto-electronics applications. Several of our mature production platforms utilize SiC and GaN microelectronics, and the potential of Ga_2O_3 combined with the accelerated strain on the national grid represents the opportunity and motivation to develop the next generation of rugged high voltage power electronics systems. Currently, Mainstream is targeting systems-level integration and testing of developmental discrete Schottky diodes (SBDs) from NCT in existing Mainstream platforms. To help advance the domestic maturity of Ga_2O_3 technology, Mainstream is coordinating development across the entire TRL spectrum with their domestically integrated Team of public-private partnerships to establish an ecosystem of Ga_2O_3-based discretes, modules, and power conversion systems. Development efforts and technology transfer are being undertaken with Penn State's Applied Research labs (Penn State ARL), a DOW UARC, and Sandia National Lab's Power Electronics Group (Sandia). Additionally, Mainstream has joined Luxium Solutions in a bid to merge substrate and epitaxy production with Mainstream's downstream production scheme to accelerate establishment of a domestic supply-chain for substrates, epiwafers, bare die, discrete devices, and modules. Mainstream's ultimate vision is to design power conversion systems from the device-level up, around the end-application's needs and requirements. Our ultimate approach is to phase in Ga_2O_3 devices in hybrid configurations where its strengths in step-up voltage are capitalized and the risk of its current limitations are mitigated. As innovation in fabrication and processing matures, we will seek to develop systems and sub-systems entirely composed of Ga_2O_3. This is the same approach used to integrate and mature SiC in the EV industry. We see Ga_2O_3 as a powerful and commercially viable enabler of next-generation power electronics systems that can address critical performance roadblocks towards high voltage transportation and grid solutions.

IWGO-MoP-48 Heteroepitaxial β-Ga_2O_3-on-SiC (GOSiC): Vertical Schottky Devices and Device-Predictive Cathodoluminescence*, Dominic Lane,* Silanna

β-Ga_2O_3 is an ultra-wide-bandgap semiconductor (band gap ≈ 4.8 eV) whose critical fieldabove 8 MV/cm gives an exceptional Baliga figure of merit for high-voltage power electronics, yet its low thermal conductivity and (currently) small diameter native substrates have limited practical vertical devices. We report buffer-free metal-organic chemical vapour deposition (MOCVD) of β-Ga_2O_3 directly on 4H-SiC (GOSiC), pairing the breakdown strength of Ga_2O_3 with the thermal conductivity, maturity and large-area supply of SiC; the small 0.2 eV conduction-band offset permits low-resistance vertical conduction [1]. A high temperature trimethylgallium preflow chemically restructures the native oxycarbide to seed direct nucleation with no interlayer, yielding phase-pure (–201) films with an ω-scan FWHM down to ~0.5° — to our knowledge the best heteroepitaxial alignment on 4H-SiC reported. Vertical Ni Schottky barrier diodes, fabricated without any field-management structures, reach a peak critical field of 1.18 MV/cm (1.06 MV/cm averaged across more than 600devices per wafer) at greater than 97% yield, matching or exceeding the best homoepitaxialβ-Ga_2O_3 reports [1].We further establish temperature-dependent cathodoluminescence (CL) as a fast, inline andnon-destructive predictor of this device performance. Sub-bandgap emission (2.6–3.9 eV) is deconvolved into five Gaussian components (P1–P5) assigned to intrinsic gallium-vacancy, divacancy and self-trapped-hole states, benchmarked against density-functional theory [2].Three CL "competition" metrics — the P1/P2 and P1/P4 intensity ratios and the thermal slope of the P1 linewidth — correlate with the device critical field at $R \geq +0.94$ ($n = 9$), well above the $|R| = 0.76$ ceiling set by AFM roughness. Each quantifies how strongly the $V^{2-}Ga$ deep acceptor radiative pathway out-competes non-radiative recombination, so a brighter deep level emission counter-intuitively marks a stronger device: CL intensity is a radiative branching ratio, not an absolute defect count. A single 300 K readout of the P1, P2 and P4 emissions thus provides a device-predictive process metric that is absent from any conventional structural diagnostic, establishing GOSiC as a manufacturable, thermally managed foundation for vertical β-Ga_2O_3 power devices.

Author Index

Bold page numbers indicate presenter

— A —
Akhtar, Arub: IWGO-MoP-30, 6
Akiba, Takayuki: IWGO-MoP-33, 6
Alonso-Orts, Manuel: IWGO-MoP-43, 8
Amano, Hiroshi: IWGO-MoP-29, 5
An, Eun-Jeong: IWGO-MoP-22, 4
An, JuEun: IWGO-MoP-4, 1
Anderson, Travis: IWGO-MoP-14, 3
Ando, Yuji: IWGO-MoP-36, 7
Ansbro, Avery-Ryan: IWGO-MoP-25, **5**
— B —
Bae, Sang-Jin: IWGO-MoP-22, 4
Bae, Si-Young: IWGO-MoP-21, 4
Bin Anooz, Saud: IWGO-MoP-30, 6; IWGO-MoP-31, 6
Binder, Andrew: IWGO-MoP-47, 9
Braun, Jeffrey: IWGO-MoP-28, 5
— C —
Callsen, Gordon: IWGO-MoP-43, 8
Chiang, Chao-Ching: IWGO-MoP-14, 3
Chikoidze, Ekaterine: IWGO-MoP-18, 3
Chou, Ta-Shun: IWGO-MoP-30, 6; IWGO-MoP-31, 6
Czuba, Krzysztof: IWGO-MoP-23, 5
— D —
Dobročka, Edmund: IWGO-MoP-34, 7
Dryden, Daniel: IWGO-MoP-40, **8**
Dumont, Yves: IWGO-MoP-18, 3
— E —
Eickhoff, Martin: IWGO-MoP-43, 8
Elhajhasan, Mahmoud: IWGO-MoP-43, 8
Esteves, D.M.: IWGO-MoP-11, 2
— F —
Fiedler, Andreas: IWGO-MoP-30, 6; IWGO-MoP-31, 6
Floyd, Richard: IWGO-MoP-47, 9
Fujita, Shizuo: IWGO-MoP-35, 7; IWGO-MoP-36, **7**
— G —
Gaskins, John: IWGO-MoP-28, 5
Ghosh, Saptarsi: IWGO-MoP-20, 4
Gołębiowska, Aneta: IWGO-MoP-23, 5
Goorsky, Mark: IWGO-MoP-8, 2
Gregušová, Dagmar: IWGO-MoP-34, 7
Grüneberg, Raimund: IWGO-MoP-30, 6
Gucmann, Filip: IWGO-MoP-34, **7**
Gurukrishna Vadlamudi, Sai: IWGO-MoP-34, 7
Guza, Marcin: IWGO-MoP-23, 5
— H —
Haberland, Kolja: IWGO-MoP-30, **6**
Handwerg, Martin: IWGO-MoP-31, 6
Haque, Aman: IWGO-MoP-14, 3
Hatayama, Eito: IWGO-MoP-10, **2**
Hendzelek, Wojciech: IWGO-MoP-23, **5**
Heron, John: IWGO-MoP-25, 5
Higashiwaki, Masataka: IWGO-MoP-39, 7
Hill, Justin: IWGO-MoP-47, 9
Holtz, Megan: IWGO-MoP-46, 8
Honda, Tohru: IWGO-MoP-33, 6
Hopkins, Patrick: IWGO-MoP-28, 5
Hušeková, Kristína: IWGO-MoP-34, 7
— I —
Ikeda, Hikaru: IWGO-MoP-36, 7
Imhof, Alecsander: IWGO-MoP-41, 8
Ishida, Kentaro: IWGO-MoP-6, **1**
Ishihara, Takuma: IWGO-MoP-7, 1
Ishikawa, Mahiro: IWGO-MoP-7, **1**
Ishiyama, Shota: IWGO-MoP-19, 4
Isobe, Yuki: IWGO-MoP-35, **7**; IWGO-MoP-36, 7
Izumi, Hirokazu: IWGO-MoP-35, 7
— J —
Jang, MinSeok: IWGO-MoP-4, 1
Jeon, Ho Jung: IWGO-MoP-16, 3
Johnson, Jesse: IWGO-MoP-47, **9**
Jung, Kwang-Hee: IWGO-MoP-22, 4
— K —
Kamiński, Maciej: IWGO-MoP-23, 5
Kanegae, Kazutaka: IWGO-MoP-10, 2
Kaneko, Kentaro: IWGO-MoP-35, 7
Kang, Jin-Ki: IWGO-MoP-22, 4
Kaplar, Bob: IWGO-MoP-47, 9
Karg, Alexander: IWGO-MoP-43, **8**
Kato, Masashi: IWGO-MoP-19, 4; IWGO-MoP-7, 1
Kern, Deborah: IWGO-MoP-31, **6**
Kezer, Pat: IWGO-MoP-25, 5
Kim, HeeJin: IWGO-MoP-4, 1
Kim, Jung-Gon: IWGO-MoP-22, 4
Kozak, Iryna: IWGO-MoP-34, 7
Krishnamoorthy, Sriram: IWGO-MoP-12, 3
Kumagai, Yoshinao: IWGO-MoP-39, 7
Kusaba, Akira: IWGO-MoP-39, 7
— L —
Labed, Madani: IWGO-MoP-16, 3
Lamb, Dan: IWGO-MoP-20, 4
Lane, Dominic: IWGO-MoP-48, **9**
Lavelle, Robert: IWGO-MoP-41, 8; IWGO-MoP-47, 9
Leach, Jacob: IWGO-MoP-14, 3
Lee, Dong-Jin: IWGO-MoP-22, 4
LEE, Eun-Seo: IWGO-MoP-22, **4**
Lee, HoJun: IWGO-MoP-4, 1
Lee, JungBok: IWGO-MoP-4, **1**
LEE, Won-Jae: IWGO-MoP-22, 4
Li, Jian-Sian: IWGO-MoP-14, 3
Liang, Yi: IWGO-MoP-25, 5
Liao, Michael: IWGO-MoP-8, **2**
Liu, Yizheng: IWGO-MoP-12, **3**
Llewelyn, Ciaran: IWGO-MoP-20, 4
Londhe, Manasi: IWGO-MoP-25, 5
Lorenz, Katharina: IWGO-MoP-11, 2
Loske, Katharina: IWGO-MoP-14, **3**
Lyle, Luke: IWGO-MoP-47, 9
— M —
Mahadik, Nadeemullah: IWGO-MoP-41, **8**
Maitra, Shreyasi: IWGO-MoP-20, 4
Makisako, Ryutaro: IWGO-MoP-36, 7
Matsui, Shunya: IWGO-MoP-33, 6
Micottis, Tom: IWGO-MoP-32, **6**
Mičušík, Matej: IWGO-MoP-34, 7
Miyake, Hiroki: IWGO-MoP-5, 1
Miyamoto, Hironobu: IWGO-MoP-33, 6
— N —
Nádaždy, Peter: IWGO-MoP-34, 7
Negoita, Mihai: IWGO-MoP-47, 9
Nishinaka, Hiroyuki: IWGO-MoP-10, 2; IWGO-MoP-19, 4; IWGO-MoP-5, 1
— O —
Onuma, Takeyoshi: IWGO-MoP-33, 6
Oshima, Takayoshi: IWGO-MoP-1, **1**
— P —
Pakes, Andrew: IWGO-MoP-20, 4
Park, Jang Hyeok: IWGO-MoP-16, 3; IWGO-MoP-21, 4
Park, Mi-Seon: IWGO-MoP-22, 4
Pastir, Greg: IWGO-MoP-47, 9
Patnaik, Akash: IWGO-MoP-18, **3**
Peres, Marco: IWGO-MoP-11, 2
Perez Tomas, Amador Perez Tomas: IWGO-MoP-9, 2
Peterson, Carl: IWGO-MoP-12, 3
Píš, Igor: IWGO-MoP-34, 7
Pohorelec, Ondrej: IWGO-MoP-34, 7
Popp, Adreas: IWGO-MoP-30, 6
Popp, Andreas: IWGO-MoP-31, 6
— R —
Rehm, Jana: IWGO-MoP-30, 6
Reilly, Caroline: IWGO-MoP-14, 3
Ren, Fan: IWGO-MoP-14, 3
Reyes, Jessica: IWGO-MoP-28, 5
Ribault, Thomas: IWGO-MoP-18, 3
Rim, You Seung: IWGO-MoP-16, 3; IWGO-MoP-21, 4
Rohnke, Marcus: IWGO-MoP-43, 8
Ronning, Carsten: IWGO-MoP-43, 8
Roqan, Iman: IWGO-MoP-11, 2
Rosenauer, Andreas: IWGO-MoP-43, 8
Rummel, Brian: IWGO-MoP-47, 9
— S —
Sacchi, Anna: IWGO-MoP-46, 8
Sacksteder, Dagny: IWGO-MoP-46, **8**
Sadowski, Oskar: IWGO-MoP-23, 5
Saha, Chinmoy: IWGO-MoP-12, 3
Saito, Aoi: IWGO-MoP-5, **1**
Sanyal, Indraneel: IWGO-MoP-20, **4**
Sartel, Corinne: IWGO-MoP-18, 3
Sasaki, Kohei: IWGO-MoP-33, 6; IWGO-MoP-7, 1
Schmidbauer, Martin: IWGO-MoP-31, 6
Schowalter, Marco: IWGO-MoP-43, 8
Scott, Ethan: IWGO-MoP-28, **5**
Shah, Piyush: IWGO-MoP-8, 2
Shimazoe, Kazuki: IWGO-MoP-19, **4**; IWGO-MoP-7, 1
Shin, Hee Won: IWGO-MoP-21, **4**
Shin, Kanghee: IWGO-MoP-16, **3**
Shintani, Michihiro: IWGO-MoP-10, 2
Snyder, David: IWGO-MoP-47, 9
Speck, James: IWGO-MoP-12, 3
Suda, Jun: IWGO-MoP-36, 7
Sugaya, Hidetaka: IWGO-MoP-36, 7
Szerling, Anna: IWGO-MoP-23, 5
— T —
Tadjer, Marko: IWGO-MoP-14, 3; IWGO-MoP-28, 5; IWGO-MoP-41, 8
Taishi, Toshinori: IWGO-MoP-6, 1
Takahashi, Hidemasa: IWGO-MoP-36, 7
Takayama, Hajime: IWGO-MoP-10, 2
Tanaka, Katsuhisa: IWGO-MoP-35, 7; IWGO-MoP-36, 7
Ťapajna, Milan: IWGO-MoP-34, 7
Tarenko, Jarosław: IWGO-MoP-23, 5
Taube, Andrzej: IWGO-MoP-23, 5
Tellekamp, M. Brooks: IWGO-MoP-46, 8
Teo, K.B.K: IWGO-MoP-20, 4
Togashi, Rie: IWGO-MoP-39, **7**
— U —
Ueda, Tetsuzo: IWGO-MoP-36, 7
Upadhyaya, Kishor: IWGO-MoP-11, **2**
— V —
Van de Walle, Chris: IWGO-MoP-12, 3
Vellvehí i Llovet, Aniol: IWGO-MoP-9, **2**
— W —
Wakamatsu, Takeru: IWGO-MoP-35, 7; IWGO-MoP-36, 7
Wan, Hsiao-Hsuan: IWGO-MoP-14, 3
Wang, Haitao: IWGO-MoP-29, 5
Wang, Haochen: IWGO-MoP-12, 3
Wang, Jia: IWGO-MoP-29, 5
Wierzbicka, Justyna: IWGO-MoP-23, 5
Williams, Martin Samuel: IWGO-MoP-43, 8
Wójcicka, Aleksandra: IWGO-MoP-23, 5
Wzorek, Marek: IWGO-MoP-23, 5
— X —
Xu, Zhiyu: IWGO-MoP-29, **5**
— Y —
Yamaguchi, Tomohiro: IWGO-MoP-33, 6
Yamamoto, Yuki: IWGO-MoP-35, 7
Yasuda, Harunobu: IWGO-MoP-33, **6**

Author Index

Yatskiv, Roman: IWGO-MoP-2, **1**
Yun, Ho-Gyun: IWGO-MoP-22, 4

— Z —
Zheng, Yunlin: IWGO-MoP-18, 3