International Workshop on Gallium Oxide and Related Materials (IWGO-6)
Room ESJ 0202 - Session IWGO-WeM2

Epitaxial Growth and Doping Control II

Moderators: Ahmad Islam, AFRL, **Sriram Krishnamoorthy**, University of California Santa Barbara

10:50am **IWGO-WeM2-35 Structural and Electrical Properties of *c*-plane α-Ga$_2$O$_3$ Grown on High-quality α-Cr$_2$O$_3$ Templates by HVPE*, Yuichi Oshima,*** *Takayoshi Oshima,* National Institute for Materials Science, Japan*; Shiyu Xiao, Kazuto Murakami, Katsuhiro Imai, Takahiro Tomita,* NGK INSULATORS, LTD, Japan

α-Ga$_2$O$_3$ is a promising power semiconductor material; however, due to its metastable nature, high-quality bulk substrates are not available. Consequently, epitaxial growth of α-Ga$_2$O$_3$ has mainly been performed on sapphire substrates with large lattice mismatch, resulting in high dislocation densities. Recently, high-quality α-Cr$_2$O$_3$ templates, which exhibit a small in-plane lattice mismatch of approximately −0.45% with *c*-plane α-Ga$_2$O$_3$, have attracted significant attention. Epitaxial growth of α-Ga$_2$O$_3$ thin films (<~1 µm) on α-Cr$_2$O$_3$ has been demonstrated using mist CVD [1] and HVPE [2], showing dislocation densities on the order of 10^7 cm^{-2}, about three orders of magnitude lower than those on sapphire substrates [1].

In this study, α-Ga$_2$O$_3$ films were grown on high-quality α-Cr$_2$O$_3$ templates to thicknesses far exceeding previously reported values, and their crystalline quality and electrical properties were investigated [3]. The films were grown by HVPE at 520 °C with thicknesses ranging from 0.24 to 21 µm and a growth rate of approximately 14 µm/h. X-ray diffraction measurements confirmed phase-pure, single-crystalline α-Ga$_2$O$_3$. The tilt angle estimated from X-ray rocking curves was close to that of the underlying α-Cr$_2$O$_3$ layer and did not increase with film thickness, while the twist angle increased for films thicker than 10 µm. The dislocation density estimated from etch pit density (EPD) was 5.6×10^7 cm^{-2} for the thinnest film. Although it increased to 3.9×10^8 cm^{-2} for the 21 µm-thick film, this value remains much lower than that of α-Ga$_2$O$_3$ layers of similar thickness grown directly on sapphire (~3×10^9 cm^{-2}).

Furthermore, Si-doped α-Ga$_2$O$_3$ films with a thickness of 2 µm and EPD of ~(1–3)×10^8 cm^{-2} were fabricated and their electrical properties were evaluated by Hall measurements at room temperature. The mobility increased with decreasing carrier concentration, reaching 144 cm^2/Vs at a carrier concentration of 1.8×10^{18} cm^{-3}. This value significantly exceeds previously reported highest mobilities of approximately 52 cm^2/Vs for *c*-plane [4] and 99 cm^2/Vs for *m*-plane α-Ga$_2$O$_3$ [5].

[1] K. Yamada et al, the 72nd JSAP Spring Meet. 14-17 Mar, 2025, Noda, Japan, 16p-Y1311-7 (2025).

[2] K. Takeda et al, 44th Electron. Mater. Symp. (EMS-44), Nara, Japan, Oct 15-17, Fr1-12 (2025).

[3] Y. Oshima et al, J. Appl. Phys. 139, 075302 (2026).

[4] H. Son et al, ECS J. Solid State Sci. Technol. 9, 055005 (2020).

[5] T. Wakamatsu et al, Appl. Phys. Lett. 128, 012105 (2026).

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11:05am **IWGO-WeM2-38 Homoepitaxial Growth on (0-1-1) *β*-Ga$_2$O$_3$ Substrates Using Oxide Vapor Phase Epitaxy*, Tomoka Nishikawa,*** The University of Osaka, Japan*; Chia-Hung Lin, Kohei Sasaki, Akito Kuramata,* Novel Crystal Technology, Inc., Japan*; Eisho Kishimoto, Tomoyuki Tanikawa, Ryuji Katayama, Shigeyoshi Usami, Masayuki Imanishi, Yusuke Mori,* The University of Osaka, Japan

β-Ga$_2$O$_3$ has a large bandgap considered suitable for high voltage power devices. Oxide vapor phase epitaxy (OVPE) enables the growth of high-purity films by utilizing Ga$_2$O gas and H$_2$O vapor as group-III and group-VI sources, respectively. We previously investigated growth conditions on the (001) and (010) planes by using OVPE; however, as macro steps occurred at the epitaxial surface due to growth rate anisotropy [1], it is necessary to improve the surface flatness by exploring different crystal orientations. In this study, we focus on the (0-1-1) (or (0-1-1)) plane, on which a flat epitaxial surface was obtained by halide vapor phase epitaxy (HVPE) [2]. (0-1-1) growth was carried out by OVPE on an edge defined film fed growth (EFG) substrate and achieved a growth rate of 5.0 µm/h (thickness: 10 µm), which is faster than that on the (001) plane (0.40 µm/h, thickness: 0.80 µm) under the same conditions. Additionally, the (0-1-1) surfece exhibited no macro–steps (Fig. 1(a)), in clear contrast to the pronounced macro-steps observed on the (001) surface (Fig. 1(b)). This result indicates that the (0-1-1) plane is promising for OVPE growth. An atomic force microscopy (AFM) image (Fig. 1(c)) revealed a root-mean-square (RMS) roughness of 11.2 nm, and streaks on the surface were observed. Pits were rarely observed on the (0-1-1) surface in OVPE (Fig. 2(a)), whereas hillocks appeared on the surface obtained by HVPE [3]. These pits were approximately 4 µm deep (Fig. 2(b)) and are considered to have facets corresponding to the (-201) and (101) planes. [1] E. Kishimoto et al., Proc. 21st Int. Conf. on Crystal Growth and Epitaxy (ICCGE-21), H26 (2025). [2] K. Goto et al., Appl. Phys. Lett. 120, 102102 (2022). [3] Y. Oshima and T. Oshima, Sci. Technol. Adv. Mater. 26, 1 (2025).

11:20am **IWGO-WeM2-41 Fe Compensation Doping and Interface Stability for Mitigating Interfacial Si Conductivity in MBE-Grown β-Ga$_2$O$_3$ Thin Films*, Brenton Noesges,*** *Prescott Evans, Jian Li,* Core4ce*; Mark Gordon,* University of Dayton*; Daram Ramdin,* Core4ce*; Nicholas Sepelak,* KBR*; Daniel Dryden,* Air Force Research Lab, Sensors Directorate*; Shin Mou, Adam Neal, Thaddeus Asel,* Air Force Research Laboratory, Materials and Manufacturing Directorate

Parasitic conduction from accumulated Si between β-Ga$_2$O$_3$ films and substrate remains a persistent challenge for β-Ga$_2$O$_3$-based devices, particularly in lateral structures. Efforts to remove this interfacial Si via various etching methods have been mostly successful, however, in oxide molecular beam epitaxy (MBE), such efforts appear unsuccessful due to re-accumulation of Si from within the MBE including the Si dopant source. Instead of Si removal, we demonstrate how a thin layer of Fe-doped β-Ga$_2$O$_3$ on the substrate surface can compensate interfacial Si and eliminate the double-channel effect from lateral devices. Secondary ion mass spectrometry (SIMS) and capacitance-voltage (C-V) measurements confirm the Fe confinement to the substrate-film interface and interfacial charge compensation, respectively. Devices fabricated from epitaxial material using this interfacial Fe compensation show no double channel effect in ~97% of structures, significantly improved from device yield of <50% without Fe compensation. These results demonstrate a potential method to mitigate parasitic conduction channels due to interfacial Si in β-Ga$_2$O$_3$. While Fe seems initially promising, we are doing further studies on the stability of the interfacial Fe-doped layers to both processing conditions and electrical cycling during device operation. Alternative compensating acceptors including N or Mg need to be explored given the observation of capacitance transients in Fe-doped structures. Overall mitigating this parasitic interface will help improve yield and performance uniformity in fabricated devices.

11:35am **IWGO-WeM2-44 Coherent Growth of α-(Al,Ga)2O3 on α-Cr2O3 Templates by Mist-CVD*, Riena Jinno,*** The University of Tokyo, Japan*; Shiyu Xiao,* NGK Insulators, Ltd, Japan*; Takayoshi Oshima,* NIMS (National Institute for Materials Science), Japan*; Satoshi Iwamoto,* The University of Tokyo, Japan*; Kazuto Murakami,* NGK Insulators, Ltd., Japan*; Katsuhiro Imai, Takahiro Tomita,* NGK Insulators, Ltd, Japan

α-(Al,Ga)$_2$O$_3$ possesses the largest bandgap of 5.4-8.8 eV among (Al,Ga)$_2$O$_3$ polymorphs, and electrical conductivity is theoretically expected when the Al composition *x* is lower than 0.7 [1].Sapphire substrates are commonly used for the growth of α-(Al,Ga)$_2$O$_3$; however, for *x*<0.7, the critical thickness is less than 50 nm, leading to high dislocation densities and consequently high resistivity [2]. α-Cr$_2$O$_3$, which is lattice matched with (Al,Ga)$_2$O$_3$, is promising as a substrate for Ga-rich α-(Al,Ga)$_2$O$_3$ growth. We previously reported the lattice-matched growth of α-(Al,Ga)$_2$O$_3$ using commercial α-Cr$_2$O$_3$ substrates, but the α-(Al,Ga)$_2$O$_3$ layers inherited the low crystallinity of the substrate [3]. High-quality α-Cr$_2$O$_3$/sapphire templates, whose dislocation density is lower than 10^8 cm^{-2}, have been realized by a group at NGK Insulators, Ltd. Dislocation density in α-Ga$_2$O$_3$ layers grown on the template were lower than 10^8 cm^{-2}, which was three orders of magnitude smaller compared to α–Ga$_2$O$_3$ films grown on sapphire substrates [4,5]. In this study, we report coherent growth of α-(Al,Ga)$_2$O$_3$ on the α-Cr$_2$O$_3$/sapphire templates.

(Al,Ga)$_2$O$_3$ films were grown on *c*-plane α–Cr$_2$O$_3$/sapphire templates manufactured by NGK Insulators, Ltd using a hot-wall-type mist-CVD system. The Al composition *x* in the grown films varied from 0.05 and 0.5. A symmetric x-ray diffraction $2\vartheta/\omega$ scan profile for the samples showed that the successful growth of single-phase α–(Al,Ga)$_2$O$_3$ on the α–Cr$_2$O$_3$ templates. Reciprocal space mapping revealed that the α–(Al,Ga)$_2$O$_3$ films with a film thickness of ca. 50 nm were coherently grown on the α–Cr$_2$O$_3$

templates when x was lower than 0.33. Surface atomic force microscopy images of the coherently grown samples revealed smooth surface roughness with root mean square roughnesses smaller than 0.12 nm. When $x = 0.09$ (almost lattice matched to α–Cr_2O_3), the flim was coherently grown on the template when the film thickness was ca. 900 nm. These findings suggest that the α–Cr_2O_3 template holds promise for the growth of high quality α–$(Al,Ga)_2O_3$ in the Ga-rich region, thus paving the way for the development of advanced α-$(Al,Ga)_2O_3$-based heterostructure devices.

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[3] R. Jinno, *et al*., IWGO-4, WeP-9 (2024).

[4] M. Watanabe, *et al*., JSAS Autumn Meet., 20p-A302-9 (2023).

[5] Y. Oshima, *et al*., J. Appl. Phys. **139**, 075302 (2026).

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11:50am **IWGO-WeM2-47 Demonstration of Homojunction Ga2O3 PiN Diodes with High Bipolar Injection***, **Pierre Gallarday**, Aniol Vellvehí, Miquel Vellvehí, José Rebollo, Josep Montserrat,* INSTITUTE OF MICROELECTRONICS OF BARCELONA - (IMB-CNM-CSIC), Spain*; Corine Sartel, Yves Dumont, Ekaterine Chikoizde,* Groupe d'étude de la matière condensée (GEMaC) - UVSQ, France*; Amador Pérez-Tomás,* INSTITUTE OF MICROELECTRONICS OF BARCELONA - (IMB-CNM-CSIC), Spain

Gallium oxide (Ga_2O_3) is widely recognized as a premier next-generation, ultra-wide-bandgap (UWBG) semiconductor for energy, power and deep-UV optoelectronics, offering a compelling pathway beyond the limits of Si, SiC, and GaN. However, to fully exploit the benefits of Ga_2O_3 in high-power applications, achieving *p*-type conductivity and, consequently, an effective *p-n* junction is mandatory. This remains as one of the major challenges of the technology.

Ion implantation technique has attracted attention to form stable *p*-type conduction when applied into epitaxial layer in homojunction systems. Very recently, vertical *p-n* junctions using Phosphorous (P) have been reported. This is an unexpected result as, in general, P implantation in β-Ga_2O_3 is regarded as amphoteric and only a deep acceptor. However, when the P doping dose is sufficiently high in the implanted regions, a delocalization-localization regime has been observed typically associated with disordered systems in Anderson-localization physics, i.e., a metal-insulation transition (MIT) at low-T that enables hole transport.

In this work, a homoepitaxial PiN diode was engineered and presents unambiguous high-injection bipolar operation. We apply the recently reported methodology of acceptor extended wavefunctions in disordered system (related to Anderson disorder) via a P implantation route performed on epitaxial highly resistive *p*-type Ga_2O_3 grown via MOCVD on commercial highly conductive Sn-doped (001) substrates. Here, we demonstrate that using a native lightly doped *p*-type intrinsic epi reduces the residual donor and increase bipolar conductivity modulation which results in an easier minority lifetime control. The consistent device demonstration of 8-6x10^{18} cm^{-3} free hole depletion and electron-hole plasma adds further evidence that bipolar devices are possible in Ga_2O_3 and confirm that P implantation is a route for implementing homoepitaxial *p-n* junctions.

In summary, our results show that the introduction of native *p*-type conductivity compensates residual donor defects, enhances bipolar conductivity modulation, and enables improved control of carrier lifetime. The reproducible observation of free-hole depletion and electron-hole plasma in the range of ~1–8× 10^{18} cm^{-3} at room *T* provides further compelling evidence for the feasibility of bipolar device operation in Ga_2O_3. In unterminated devices, it is yet possible to achieve minority carrier lifetimes of 0.1-0.2 ms, current densities above 6000 A/cm^2, breakdown voltages larger than 500V and on-off ratios of 10^7. These results open new research avenues toward advanced Ga_2O_3 power electronic devices based on disordered extended waveform concepts.

12:05pm **IWGO-WeM2-50 Uniform Growth of Thick Homoepitaxial β-Ga_2O_3 Layers on 2-inch (010) Substrates by Low-Pressure Hot-Wall MOVPE***, **Yoshiki Iba**, Yuma Terauchi,* Tokyo University of Agriculture and Technology, Japan*; Junya Yoshinaga,* TAIYO NIPPON SANSO CORPORATION, Japan*; Yasuhiro Hashimoto,* Sumitomo Metal Mining Co. Ltd., Japan*; Yoshinao Kumagai,* Tokyo University of Agriculture and Technology, Japan

β-Ga_2O_3 is a promising candidate material for next-generation power devices. The growth of thick homoepitaxial layers with controlled conductivity is essential for vertical device fabrication. Recently, our group demonstrated high-speed growth of Si-doped n-type homoepitaxial layers with a carrier concentration of 2 × 10^{16} cm^{-3} on β-Ga_2O_3(010) small-sized substrates (10 × 15 mm^2) by low-pressure hot-wall metalorganic vapor phase epitaxy (MOVPE) [1]. In this study, homoepitaxial growth was carried out on 2-inch β-Ga_2O_3(010) substrates, and the crystallinity and uniformity of the grown layers were investigated.

A horizontal low-pressure hot-wall MOVPE reactor (TAIYO NIPPON SANSO, FR2000-OX) was used. Si-doped homoepitaxial layers were grown on a 2-inch-diameter Sn-doped β-Ga_2O_3(010) substrate for 150 min at a reactor pressure of 3.4 kPa and a growth temperature of 1000ºC using trimethylgallium (TMGa), O_2, and tetramethylsilane (TMSi) as the Ga, oxygen, and Si dopant sources, respectively, using Ar as the carrier gas.

An approximately 11 µm-thick homoepitaxial layer with a smooth surface was obtained over the entire substrate. The X-ray rocking curves of β-Ga_2O_3(020) measured at various positions on the 2-inch substrate all exhibited full width at half maximum (FWHM) values in the range of 27–38 arcsec, comparable to those of the original substrate. Furthermore, secondary-ion mass spectrometry measurements revealed a uniform Si doping concentration of approximately 1 × 10^{16} cm^{-3} at all measured positions, suggesting that the prepared homoepitaxial substrate is suitable for device fabrication.

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[1] J. Yoshinaga *et al*., Appl. Phys. Express **18**, 055503 (2025).

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