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

Room ESJ Concourse - Session IWGO-TuP

IWGO Poster Session II

Moderator: A F M Anhar Uddin Bhuiyan, University of Massachusetts Lowell

IWGO-TuP-2 Cathodoluminescence Study of Rutile GeO_2 Grown via Mist CVD, ***Kazuki Shimazoe***, *Shota Ishiyama,* Nagoya Institute of Technology, Japan*; Kazutaka Kanegae, Hiroyuki Nishinaka,* Kyoto Institute of Technology, Japan*; Masashi Kato,* Nagoya Institute of Technology, Japan

Ultrawide bandgap (~4.6 eV) rutile germanium dioxide (r-GeO_2) has attracted significant attention as a high-power switching device material owing to its large breakdown field (~7 MV/cm) and ambipolar doping ability. Schottky barrier diode and transistor operations have been reported using r-GeO_2 thin films and bulk substrates, respectively [1,2]. Defect characterization is essential for achieving reliable device operation. Cathodoluminescence (CL) is powerful technique to examine defect-related luminescence in wide bandgap semiconductors. This study investigated CL properties of GeO_2 thin films to understand the defects.

Mist chemical vapor deposition (CVD) was utilized for growth of GeO_2 thin films. (001) TiO_2 was used as the growth substrate. Graded $Ge_xSn_{1-x}O_2$ buffer layers were inserted to grow single-phase r-GeO_2. The details of the graded buffer layer have been reported elsewhere [3]. Figure 1 shows the CL spectra of r-GeO_2 grown on a graded $Ge_xSn_{1-x}O_2$ buffer layer, along with the spectrum of the graded buffer layer alone for comparison. Luminescence peaks attributed to r-GeO_2 were observed around 2.2, 3.8, and 4.4 eV. The peak around 2.2 eV is close to the peak attributed to oxygen deficient centers [4]. The luminescence around 4.4 eV is relatively close to the bandgap of r-GeO_2 (~4.6 eV) although its transition is forbidden. One possibility is luminescence originating from isoelectronic traps associated with carbon impurities derived from the mist CVD precursor ($C_6H_{10}Ge_2O_7$). The incorporation of carbon into r-GeO_2 was confirmed by energy dispersive X-ray spectroscopy. Another possibility is that non-ideal crystallinity, such as defects or strain in the film, breaks the selection rules, thereby enabling forbidden transition to be observed. In the presentation, we will discuss more detailed CL results using temperature dependent spectra.

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IWGO-TuP-4 Influence of Sapphire Substrate Orientation on Epitaxial Rutile GeO2 Thin Film Solar-Blind Photodetector Properties, ***Eriks Dipans***, *Edvards Strods, Sven Oras, Annamarija Trausa, Jevgenijs Gabrusenoks, Edgars Butanovs,* Institute of Solid State Physics, University of Latvia

Rutile GeO2 (r-GeO2) has recently emerged as a promising ultrawide-bandgap (Eg~4.7 eV) semiconductor due to its potential use as a solar-blind UV-C range photodetector and its theoretically predicted ambipolar doping, which implies unique device fabrication possibilities. However, producing phase pure r-GeO2 still remains challenging due to many unknown variables both in substrates and deposition methods [1]. In this work, pulsed laser deposition process for r-GeO2 thin film growth on a-, m- and r-plane sapphire substrates was demonstrated in 350 – 425 °C temperature range, and film crystallinity and morphology optimization was performed. X-ray diffraction (XRD), X-ray photoelectron spectroscopy, scanning and transmission electron microscopies, atomic force microscopy (AFM), Raman spectroscopy and ellipsometry were used for the as-grown film characterization. XRD analysis revealed that (101)-orientated r-GeO2 films were obtained on a- and r-plane sapphire substrates, while (002) orientation for m-plane substrate was observed. At optimized deposition conditions for each substrate orientation, XRD omega scan peak full width at half maximum and root mean square AFM surface roughness scan yielded results of 0.66°/5.1 nm, 0.50°/2.7 nm and 1.20°/6.9 nm for a-, m- and r-plane substrates, respectively. Furthermore, photodetector devices fabricated on these films exhibited peak responsivities 1.76 mA/W, 1600 mA/W and 5.77 mA/W for a-, m- and r-plane substrates, accordingly. It was observed that the responsivity peak wavelength at 220-230 nm for all the prepared films corresponds to a value significantly larger than the optical bandgap, which merits to be investigated further.

IWGO-TuP-5 Effect of Unintentional Si Impurities on F-doped β-Ga_2O_3 Thin Films Grown by Mist CVD, ***Ichiro Seike***, Kyoto Institute of Technology, Japan*; Hiroki Miyake,* MIRISE Technologies Corporation, Japan*; Hiroyuki Nishinaka,* Kyoto Institute of Technology, Japan

Controlling carrier concentration by doping is important for device applications of β-Ga_2O_3, which has attracted attention as a next-generation power device material. Si, Ge, and Sn have been actively studied as n-type dopants substituting the Ga site. However, there have been few experimental reports on F substituting the O site, even though theoretical calculations suggest that F is a shallow donor. Establishing the Osite doping technology in β-Ga_2O_3 is important because it may be possible to further improve conductivity by dual doping, which has been reported in ZnO and SnO_2. In this study, we report on the effect of unintentional Si impurities in F-doped β-Ga_2O_3thin films.

Figure 1(a) and (b) show the concentration of incorporated elements in F-doped β-Ga_2O_3 thin films grown using a quartz and an alumina tube in the reaction chamber, respectively. In the case where the quartz tube is used, Si concentration in the thin film is about 2×10^{20} cm^{-3}, which is much larger than the F concentration of about 2×10^{18} cm^{-3}. Since the carrier concentration calculated from Hall effect measurement at room temperature is 1.3×10^{20} cm^{-3}, it is suggested that Si contributes as a donor.This is considered to be due to the incorporation of a large amount of Si originating from the quartz tube as a result of the etching effect of F.On the other hand, when an alumina tube is used, Si concentration was reduced to 2×10^{18} cm^{-3}, a reduction of approximately two orders of magnitude compared to the quartz tube. Considering the carrier concentration of 1.6×10^{19} $cm^{-3}$by Hall effect measurement, it is thought that F contributes as a donor, unlike in the case of the quartz tube.

IWGO-TuP-6 First Demonstration of p-type LiGa5O8 UWBG Thin Films by MOCVD, ***Dong Su Yu***, *Mingxuan Wu, Binzhi Liu, Md Mosarof Hossain Sarkar, Kaitian Zhang, Jinwoo Hwang, Hongping Zhao,* The Ohio State University

Ultrawide bandgap (UWBG) $LiGa_5O_8$ with spinel cubic structure was recently discovered as a p-type material [1]. Due to the lack of native p-type Ga_2O_3, p-$LiGa_5O_8$ is considered as a promising candidate to form Ga_2O_3/$LiGa_5O_8$ pn junctions. Previously, the growth of p-$LiGa_5O_8$ has been demonstrated via mist-CVD [1].

In this work, we achieve the first successful growth of p-$LiGa_5O_8$ via metalorganic chemical vapor deposition (MOCVD). Triethylgallium (TEGa), lithium-tert-butoxide (LiOtBu), and high-purity oxygen are used as the Ga, Li and O precursors, respectively. Both c-sapphire and GaN-on-sapphire are used as substrates. X-ray diffraction measurements indicate the formation of peaks consistent with the cubic spinel $LiGa_5O_8$ phase. Cross-sectional scanning transmission electron microscopy revealed well-crystallized $LiGa_5O_8$ thin films with lattice structures consistent with the cubic spinel.X-ray photoelectron spectroscopy analysis confirmed the lithium incorporation in samples with relatively high Li molar flow rates. Electrical transport properties were probed using room temperature Hall measurements. The as-grown films show a wide range of resistivity depending on the MOCVD growth condition. For a selected series of samples, the Hall measurements show p-type conduction with hole concentrations on the order of ~10^{18} cm^{-3} and mobility around ~10 $cm^2/V{\cdot}s$.

Results from this work demonstrate the feasibility of $LiGa_5O_8$ growth by MOCVD and provide initial insight into growth conditions and carrier transport in this material system. The present study proposes a promising route to integrate p-$LiGa_5O_8$ with Ga_2O_3 power device technologies.

IWGO-TuP-7 Fabrication and Characteristics of α-Ga_2O_3-Based Schottky Barrier Diodes on Sapphire Substrates for Microwave Rectenna Applications, *Takeru Wakamatsu,* Kyoto University, Japan*; Yasuo Ohno,* Laser Systems Inc., Japan*; Hikaru Ikeda,* ***Shizuo Fujita***, Kyoto University, Japan*; Tomomi Hiraoka,* Laser Systems Inc., Japan*; Kentaro Kaneko,* Ritsumeikan University, Japan*; Katsuhisa Tanaka,* Kyoto University, Japan

Rectennas are key devices in microwave wireless power transfer converting RF to DC using a rectifier and an antenna. To obtain higher conversion efficiency of a rectifier, the product of R_{on}(on-resistance) and C_{off} (capacitance in the off-state) should be minimized. Ga_2O_3 is a promising material owing to its high breakdown field (E_c), since there is the relationship $R_{on}C_{off} = 2V_{out}/\mu E_c^2$, where μ denotes the mobility. Furthermore, sapphire substrates are suitable for RF applications due to their low dielectric loss, and therefore rectifiers made of α-Ga_2O_3, which is grown on sapphire using mist CVD, can enable the integration of a rectifier, an

antenna, and a matching circuit onto a single chip. In this presentation, we demonstrate the fabrication and RF characteristics of α-Ga_2O_3 Schottky barrier diodes (SBDs) for use in rectennas.

α-Ga_2O_3 SBDs consisting of n^- and n^+ layers, with ananode diameter of 4 μm, were fabricated on sapphire substrates by mist CVD with Ge doping. *C-V* measurements revealed the net donor concentrations of 4×10^{17} and 8×10^{18} cm^{-3} for the n^- and n^+ layers, respectively. The anode is connected to the anode pad via an air bridge to minimize $R_{on}C_{off}$. The *I-V* characteristics of the SBD indicated an ideality factor of 1.07, an on-resistance of 210 Ω, and a breakdown voltage of 41.4 V. The capacitance in the off-state (C_{off}) was estimated to be 0.02 pF based on the *S*-parameters in the off-state.

A full-wave rectifier circuit comprising 16 SBDs arranged in a 4´4 configuration was fabricated and used for RFcharacterization. A 2.45 GHz microwave signalwas delivered to the rectifier circuit via an RF probe. The input power to the rectifier circuit (P_{in}) and the reflected power (P_{ref}) were measured using directional couplers. The output power (P_{out}) was obtained from the DC output voltage (V_{out}) across the 1 kΩload resistance (R_{load}) as $P_{out} = V_{out}^2/R_{load}$.The results revealed a conversion efficiency of 13.9 % at an input power of 1.7 W. However, the efficienciesare significantly underestimated due to on-chip measurements without a matching circuit, resulting in high reflectance. We created a circuit model using the S-parameters of a single SBD and incorporating an impedance-matching circuit; this predicted a conversion efficiency of 67 % at an input power of 1 W. These results encourage the use of α-Ga_2O_3 SBDs on sapphire for RF rectennas for microwave wireless power transfer systems.

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IWGO-TuP-8 Gigantic Space Charge Limited Currents and Thermal Effects in Si-Fe-doped Ga_2O_3 Devices, ***Pierre Gallarday***, *Aniol Vellvehí,* INSTITUTE OF MICROELECTRONICS OF BARCELONA - (IMB-CNM-CSIC), Spain*; Verena Leitgeb,* Department Microelectronics, Materials Center Leoben Forschung GmbH (MCL), Austria*; Miquel Vellvehí, Josep Montserrat,* INSTITUTE OF MICROELECTRONICS OF BARCELONA - (IMB-CNM-CSIC), Spain*; Barbara Kosednar-Legenstein, Lisa Mitterhuber, Elke Kraker, Anton Köck,* Department Microelectronics, Materials Center Leoben Forschung GmbH (MCL), Austria*; José Rebollo, Amador Pérez-Tomás,* INSTITUTE OF MICROELECTRONICS OF BARCELONA - (IMB-CNM-CSIC), Spain

Currents, far in excess of ohmic currents, can be drawn through thin, relatively perfect insulating crystals being the solid-state analog of space charge limited current (SCLC) phenomena in a vacuum diode. SCLC is most relevant in materials with low intrinsic carrier density and weak screening, such as organic semiconductors, insulators, and wide bandgap materials, where it helps probe mobility and defect states. Two basic requirements were established to observe SCLC in low conducting materials: (i) at least one of the contact must be ohmic to provide an excess of carriers ready to enter the material and (ii) the studied material has to be relatively free from trap states.

In this work, we investigate the electro-thermal behaviour due to unusual and gigantic SCLC transport of an (010)-oriented high-resistivity compensated Fe-doped β-Ga_2O_3 as-received single crystal with a compensating shallow Si-implant and lateral concentric metal ohmic contacts (Ti/Au). The Si-channel implantation (depth ~300nm) was defined via BOX profile technique with energies of 200 keV, 95 keV, 60 keV, 30 keV and 10 keV, and with doses in the range of 1.28×10^{13}- 0.6×10^{12} ions/cm^2. Physical characterization includes XRD and Raman –showing no implantation structural effect- while thermal analysis is done by Time-Domain Thermo Reflectance (TDTR). TDTR reveals a substantial reduction in thermal conductivity within the implanted layer (12.5 W/mK - implanted vs 20.2 W/mK - bulk), attributed to lattice disorder and increased phonon scattering.

A simplified analytical model describing the spatial distribution of electric field and volumetric Joule heating under SCLC conditions shows good agreement with electrical measurements, i.e., current is proportional to V^2 and inversely to L^3 for the applied voltage and spacing between electrodes, respectively. We ascribe it to a SCLC phenomenon (Mott-Gurney) in cylindrical coordinates:

$$I=\theta\cdot(9\pi/4)\cdot\varepsilon_s\cdot\mu\cdot d_{ch}\cdot(V^2/[F\cdot r_o^2])$$

(θ - current enhancement factor, ε_s - dielectric permittivity, μ - carrier mobility, d_{ch} - conductive channel depth, F - geometrical correction in function of inner (r_i)and outer (r_o) radius).The interplay between SCLC conduction and non-uniform electric field distribution produces highly localized Joule heating, leading to pronounced temperature gradients and premature thermal breakdown at relatively low applied voltages. These findings reveal unusual enhanced electro-thermal effects in β-Ga_2O_3 devices which provides better understanding of the SCLC phenomena but may also have novel potential applications in areas such as solid-state local heating or surfaces including self-cleaning/antibacterial functional aspects.

IWGO-TuP-9 Conductive Si-doped β-Ga_2O_3 by Atomic Layer Deposition and Annealing, ***Katie Gann***, *Benjamin Greenberg, Daniel Pennachio,* Naval Research Laboratory*; Jeffrey Woodward,* Naval research Laboratory*; Alan Jacobs, Emma Rocco, Boris Feygelson, Rachael Myers-Ward, Karl Hobart, Michael Mastro,* Naval Research Laboratory

While many methods for growth of high-quality Si-doped Ga_2O_3 have been developed, epitaxial thin film growth often requires etching and complicated processing for device fabrication. This process could be simplified by conformal deposition methods, but are often limited by low crystal quality. Atomic layer deposition (ALD) of Si-doped Ga_2O_3, with trimethylgallium and ozone precursors was performed at a T_{sub}=220 °C on semi-insulating (010) β-Ga_2O_3 substrates, with 399 cycles of Ga_2O_3 and 1 cycle of Si, yielding a film thickness of 28 nm by ellipsometry and an average Si concentration of 9.5×10^{19} cm^{-3}. Characterization by HRXRD suggests the as-deposited film is amorphous. Annealing at 900 °C for 10 minutes under an N_2 ambient results in conductive films with a mobility of 49 cm^2/Vs and an estimated carrier concentration of 8.4×10^{18} cm^{-3} (roughly 9% active). XRD shows an unexpected peak around 64.2°, often attributed in literature to the 440 reflection of the γ-phase, which is considered to have a common oxygen lattice and continuous phase transformation with the β-phase. Annealing at 1000 °C resulted in the disappearance of this secondary XRD peak, but the film became insulating.

HAADF-STEM studies of the 900 °C annealed film revealed a crystallization front from the substrate, with half of the deposited film epitaxially registered with the substrate with no evidence of the original interface. Roughly ~15 nm near the free surface appeared crystalline and either of a different phase or orientation of β-Ga_2O_3. While viewing down the [001] zone axis (ZA) of the substrate, the surface region of the ALD film was identified as the [010] ZA of β-Ga_2O_3 (with [001] oriented in the surface normal), rather than any orientation of the γ-phase. While the observation of a different orientation of the β on a β-Ga_2O_3 substrate is surprising, the orientation of this thin film layer is such that the oxygen lattice is continuous, with the FCC-like stacking preserved between the two orientations. The 20-4 reflection, which corresponds with the [001] direction, is also located at 64.2°, indicating the secondary XRD peak is likely due to this orientation of β-Ga_2O_3. The observation of the common oxygen lattice suggests that the continuous transformation between β and γ phase enables this formation of a different orientation. Imaging of the electrically insulating 1000 °C annealed film showed complete recrystallization of the lattice with no evidence of a substrate-film interface. The lack of conductivity suggests either Si segregated during crystallization or compensating defects formed.

IWGO-TuP-10 Atomic Scale Investigation of (100) Twin Boundary in EFG-Grown Sn-Doped β-Ga_2O_3, ***Mehidi Hassan***, *Binzhi Liu, Jinwoo Hwang,* Ohio State University

This work presents an atomic scale investigation of the detailed structure of twin boundaries in an EFG-grown Sn-doped β-Ga_2O_3 with 0.5 mol% Sn doping. It has been known that the twin structure of β-Ga_2O_3, a highly anisotropic monoclinic crystal, not only involves the typical mirror symmetry, but also includes a lattice translation component along the twin boundary, possibly on the order of 1/4 or 1/2 of the unit cell [1]. More recent computational studies have also proposed detailed atomic structures of twin boundaries [2]. However, a detailed experimental analysis is still necessary to gain a comprehensive understanding of the formation mechanism of twins during EFG growth. In this work, we used high-resolution scanning transmission electron microscopy (STEM) to investigate such details.

Optical reflection and Electron backscatter diffraction (EBSD) was first utilized to locate the TB region. Then STEM results from the prepared FIB lamellae reveal two key aspects of the twin boundary structure. First, the structures are consistent with those predicted by Mengen et al. [2], namely (100)A and (100)B types, but the experimental results reveal specific aspects of the boundary that have not been considered in the calculations. First, there is a notable atomic scale strain near the boundary, showing deviation from the bulk structure. Second, this apparent strain at the

interface makes the twin boundary effectively an alternating twin boundary that consists of both (100)A and (100)B types, as shown in Fig. 1a. Our results suggest that, besides the energetics of the twin boundaries in β-Ga_2O_3, there are additional factors involving mismatch between the crystals, which result in the strain near the twin boundary observed in this study. The details of the twin boundary structure, strain, and a possible explanation of how this leads to two types of boundaries separated by only a few nanometers will be discussed in this presentation.

IWGO-TuP-11 Optimized CMP Processing and Subsurface Damage Control for High-Quality (010) β-Ga_2O_3 Single Crystals, *Won-Jae Lee,* ***Eun-Jeong An****, Eun-Seo Lee, Sang-Jin Bae, Ho-Gyun Yun, Kwang-Hee Jung, Jung-Gon Kim, Mi-Seon Park,* Dong-eui university, Busan, Republic of Korea*; Jin-Ki Kang, Dong-Jin Lee,* Axel, Republic of Korea

The post-processing crystalline quality of β-Ga_2O_3 single crystals grown by the vertical Bridgman (VB) method was evaluated. Raman spectroscopy revealed that while the (001) and (100) planes exhibited excellent crystallinity, high full width at half-maximum (FWHM) values for the $A_g(3)$ phonon mode was observed on the (010) surface. Furthermore, as shown in Fig. 1(a), high-resolution X-ray diffraction (HR-XRD) analysis of the (010) plane and its asymmetric (310) plane showed a consistent trend, with the (010) surface exhibiting significantly higher FWHM values. These discrepancies in crystallinity were confirmed to originate from orientation-specific sub0surface damage (SSD). The lower mechanical strength of the (010) plane makes it susceptible to fracture propagation during processing, resulting in deeper SSD than other orientations [1].

In this study, a systematic three-step chemical mechanical polishing (CMP) process was developed to effectively eliminate this deep SSD. The first CMP step used a slurry containing ~3 μm diamond and alumina abrasives with the pad A; the second CMP step used a 72 nm colloidal silica slurry with pad A; and the third CMP step used the same slurry as the second CMP step with pad B. In each step, material removal rates (MRRs) of 5, 3, and 2 μm/h, respectively. As shown in Fig.1 (b) and (c), HR-XRD analysis conducted after all processing steps confirmed the complete removal of the SSD, with the FWHM ultimately reaching 33 arcsec. Atomic force microscopy (AFM) revealed an average roughness (Ra) of 0.116 nm, indicating a surface roughness suitable for epitaxial substrates.

IWGO-TuP-12 Heat-resistant Characteristics of Li doped NiO Films Deposited by RF Magnetron Sputtering, ***Shunya Matsui****, Harunobu Yasuda, Tomohiro Ymaguchi, Tohru Honda,* Department of Electrical Engineering and Electronics, Kogakuin University, Japan*; Hironobu Miyamoto, Kohei Sasaki,* Novel Crystal Technology, Japan*; Takeyoshi Onuma,* Department of Electrical Engineering and Electronics, Kogakuin University, Japan

β-Ga_2O_3 is expected as a next-generation material to replace existing Si and SiC, but achieving p-type conductivity remains elusive[1,2]. NiO is a possible alternative for the p-type material. However, the heat-resistance of undoped NiO is limited toaround 200℃[3]. In this study, impact of deposition conditions on resistivityρ in RF magnetron sputtering of lithium-doped NiOand their heat-resistant characteristics are shown.

24.4-227-nm-thick NiO:Li films were deposited on c-plane sapphire or quartz glass substratesfor 5 minutes in an Ar and O_2 mixture atmosphere at an ambient temperature. To dope Li atoms, a NiO target was co-sputtered with3 or 5 pieces of f=10 mm $LiNiO_2$ pellets. RF power, sputtering pressure, and O_2 ratio [O_2/(Ar+O_2)] were varied in ranges of 75-300 W, 0.25-1.50 Pa, and 0-50%, respectively. ρ was measured by the four-point probe method with van der Pauw configuration for 5×5 mm^2 square-shaped devices.Thermal annealing was conducted using tubular furnace at temperatures T_{anneal} of 400, 500, 600, and 700℃ for 20 minutes in an oxygen atmosphere with a flow rate of 0.5 L/min.

Li concentrations were evaluated by secondary ion mass spectrometry to be $1.8*10^{21}$ and $1.0*10^{22}$ cm^{-3} for the as-deposited films with 3 and 5 pellets, respectively. As shown in Fig. 1, as-deposited 5-pellet films exhibited ρ=5.26×10^{-2}-7.27×10^{-2}Ω×cm. In contrast, as-deposited 3-pellet films exhibited monotonical decrease in ρ from 1.72×10^{0} to 9.18×10^{-2}Ω×cm with increasing O_2 ratio. After the thermal annealing, r for the 5-pellet films almost unchanged below T_{anneal}=600℃, but it significantly increased at T_{anneal}=700℃. For the 3-pellet films, ρincreased up to the value obtained for the as-deposited film with O_2 ratio of 0% below T_{anneal}=600℃, but it also significantly increased at T_{anneal}=700℃.Seebeck effect measurements showed p-type conductivity for all the films. The results brought us to determine heat-resistance temperature being around 600℃. The heat-resistance of the NiO thin film was improved through Li doping.

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IWGO-TuP-14 Large-Area, UVC Passive Pixel Sensors based on Heteroepitaxial β-Ga_2O_3, *HyoJung Kim, SiSung Yoon,* ***GeonWook Yoo****,* Soongsil University, Republic of Korea

Ultraviolet-C (UVC) sensors are essential optoelectronic devices for fire detection, sterilization, environmental monitoring, and defense systems, as they detect signals that cannot be obtained by visible or infrared sensors [1, 2]. In this study, we demonstrated a β-Ga_2O_3 UVC passive pixel sensor (PPS) by integrating a β-Ga_2O_3 transistor and a large-area metal-semiconductor-metal (MSM) photodetector (PD) on a single pixel.

Fig. 1 (a) shows schematic and layout of the fabricated β-Ga_2O_3 PPS. Fig. 1(b) presents the I–V characteristics of the MSM PD (1x1 mm^2), where the dark current of 6.5 pA and a 250 nm photocurrent of 0.5 μA were measured at 20 V, resulting in a photo-to-dark contrast ratio of 10^5. Fig. 1 (c) shows a peak responsivity of 1.9 A/W at 250 nm with a UV/visible rejection ratio ($R_{250\,nm}$ / $R_{400\,nm}$) of 2.8×10^5. Fig. 2(a) presents transfer characteristic of the fabricated Ga_2O_3 transistor for V_{DS}=1, 10 V. The threshold voltage was extracted to be 3.5 V, and on/off ratio was 10^7;Fig. 2(b) shows output characteristic. R_{on} was extracted to be 0.42 kΩ·mm. Fig. 3 illustrates semi-log scale output I-V characteristics of the PPS with/without UVC (250 nm) irradiation. The gate electrode of transistor was used for a select (SEL) signal, and drain electrode was used for an output signal. For a fixed V_{SEL} of 3 V, V_{OUT} was swept from 0 to 7 V. In the dark state, the output current was ~ 90 pA, whereas under UVC irradiation, it increased to 6.2 nA. The β-Ga_2O_3 PPS showed good UVC response with a dark-to-photo current ratio of ~ 60 under irradiation of 250 nm UVC.

In summary, we demonstrated a homogeneous integration of β-Ga_2O_3 UVC PPS with a β-Ga_2O_3 MSM PD and a transistor. The MSM exhibited a high responsivity of 1.9 A/W and rejection ratio of 2.8×10^5, while the transistor showed a threshold voltage of 3.5 V for enhancement-mode and R_{on} of 0.42 kΩ·mm. The integrated PPS achieved a distinct UV response with an on/off ratio of 60. These results can provide a method to realize a monolithic integration of theheteroepitaxial β-Ga_2O_3 UVC PPS and its array toward UVC imaging.

IWGO-TuP-15 Heteroepitaxial Growth of β-Ga2O3 on High-Angle Off-Cut Sapphire via MOCVD: Optimization through Minimum Oxygen Distance Simulations, ***Hyeong-Yun Kim****, JungHun Choi, Ji-Hyeon Park, Dae-woo Jeon,* Korea Institute of Ceramic Engineering and Technology, Republic of Korea

Beta-gallium oxide (β-Ga_2O_3) is a premier ultra-wide bandgap semiconductor (> 4.9 eV) tailored for advanced high-power devices and solar-blind photodetectors. While homoepitaxial techniques on native substrates have matured, the exorbitant expense of single-crystal β-Ga_2O_3 severely restricts its commercial viability. Consequently, the heteroepitaxial deposition of β-Ga_2O_3 on sapphire via metal-organic chemical vapor deposition (MOCVD) has become a focal point of research, offering a highly scalable and economically viable pathway.

In this study, we investigate strategies to mitigate lattice mismatch and suppress the formation of rotated domains during the heteroepitaxy of β-Ga_2O_3 on sapphire. We utilized a-plane off-cut sapphire substrates to enforce structural symmetry and align these domains. While conventional approaches typically report optimal growth near a 6° off-cut, our research systematically expanded the experimental range from 6° to 16°, revealing a positive trend of improving crystallinity at these higher off-cut angles. To interpret the underlying mechanism driving this tendency at angles above 6°, we conducted comprehensive simulations based on the minimum oxygen-to-oxygen (O-O) distance between the sapphire substrate and the β-Ga_2O_3 layer. By elucidating these interactions, this work establishes an optimized framework for enhancing the crystal quality of β-Ga_2O_3 on highly off-cut sapphire, ultimately advancing the commercial viability of cost-effective UWBG power semiconductor devices.

IWGO-TuP-16 Defect- and Dopant-engineered p-type Conductivity in Epitaxial $ZnGa_2O_4$ Spinel Oxide Thin Films, *Mohammad M. Afandi, Yeongmin Park, Gyeong Ryul Lee,* ***Roy B. Chung****,* Kyungpook National University, Republic of Korea

Spinel $ZnGa_2O_4$ (ZGO) is an ultrawide-bandgap (UWBG) oxide with high optical transparency, large breakdown fields, tunable electrical conductivity,

and strong chemical stability, making it a promising candidate for high-power and extreme-environment electronics. However, achieving stable p-type conductivity remains challenging due to the self-compensation of acceptor defects in oxide semiconductors. In this study, epitaxial ZGO thin films were grown on c-plane α-Al_2O_3 substrates via mist chemical vapor deposition, with the Zn/Ga precursor ratio systematically controlled to regulate defect formation in the spinel lattice.

Structural analysis confirms the formation of highly crystalline, single-phase epitaxial films with smooth surfaces. Electrical characterization reveals stable p-type conductivity with a hole mobility of 4.43 $cm^2 V^{-1} s^{-1}$ and hole concentration on the order of 10^{15} cm^{-3} at room temperature, attributed to intrinsic self-doping arising from cation non-stoichiometry and antisite defects, supported by cation state analysis. In addition to intrinsic defect engineering, extrinsic acceptor doping using Li and Ni was preliminarily explored to further tune the electrical properties. These results highlight the importance of defect engineering in spinel oxides and establish ZGO as a promising p-type UWBG semiconductor for next-generation high-power and optoelectronic devices.

IWGO-TuP-17 Remote Epitaxy of α-Ga_2O_3 via Polycrystalline MoS_2, *Gyeong Ryul Lee,* ***Yeongmin Park****, Roy Chung,* Kyungpook National University, Republic of Korea

Among various studies on thin film growth mediated by two-dimensional (2D) materials with van der Waals bonding in the vertical direction, research on remote epitaxy has gained significant attention, beginning with the use of single-crystalline graphene. [1] Although graphene is the most extensively studied van der Waals material to date, its limited direct synthesis on various substrates and the potential damage during the transfer process pose challenges for large-area fabrication and broader material integration. Among 2D materials, transition metal dichalcogenides (TMDs), which possess a characteristic sandwich-like structure, have been reported to be synthesized over large areas using solution-based methods. [2,3] Notably, the remote epitaxial growth of ZnO nanorods using MoS_2 as a mediating layer has been demonstrated. [4] In this study, polycrystalline MoS_2 with a sandwich structure was directly synthesized on sapphire substrates with a corundum structure via a solution-based process. Using this MoS_2 layer, α-Ga_2O_3, a polymorph of Ga_2O_3 with the same crystal structure as the underlying sapphire substrate was successfully grown via remote epitaxy. To investigate the growth mechanism of Ga_2O_3 through remote epitaxy, we analyzed the microcrystal formation in the early stages of growth on both bare sapphire and MoS_2-coated substrates with varying MoS_2 thicknesses, and compared the crystalline quality of the resulting thin films. Scanning transmission electron microscopy (STEM) analysis revealed that the film began to grow as a single crystal from the interface. Finally, through exfoliation of the grown films, it was confirmed that single-crystalline Ga_2O_3 was obtained without damaging the underlying 2D MoS_2 layer.

IWGO-TuP-18 β-Ga_2O_3 Growth on Single Crystal Diamond (111), *Arpit Nandi,* University of Bristol, UK*; Arnab Mondal, Ankush Bag,* Indian Institute of Technology Guwahati, India*;* ***Martin Kuball****,* University of Bristol, UK

Gallium oxide (Ga_2O_3) enables highly efficient power electronics due to its ultra-wide bandgap and high critical electric field (8 MV/cm). However, its lack of p-type doping and poor thermal conductivity limit high-power device performance. Overcoming this requires heterointegrating Ga_2O_3 with p-type substrates such as SiC and, especially, diamond, which provides a >200-fold increase in thermal conductivity [1,2].

We report the epitaxial growth of β-Ga_2O_3 thin films on diamond substrates using a close-injection showerhead metal-organic chemical vapour deposition method. Growth on diamond in oxygen-rich environments is complicated by rapid surface oxidation of the substrate, often leading to self-exfoliation or peel-off; thus, a two-step growth approach was adopted. A low-temperature (AlxGa(1-x))2O3 (AGO6) buffer layer was used to protect the diamond surface and as a strain-relief layer, followed by high-temperature growth of the Ga_2O_3 epitaxial layer [3]. Initial growth of ($2\bar{0}1$) β-Ga_2O_3 on (001) diamond showed two-sets of in-plane grain variants. Analysing the in-plane relationship between variants, we find that using offcut (111) diamond reduces these variants. Textured epitaxy of ($2\bar{0}1$) β-Ga_2O_3 was confirmed using XRD. ϕ-scans showing increased peak separation, and reduced in-plane variants with an improved epi-layer FWHM of 0.9° on (111) diamond, down from the 1.5–1.9° typical of (001) substrates. AFM showed coalescence with a surface roughness of 4.4 nm for an area of 10x10 μm^2. We also report β-Ga_2O_3 on diamond photodetectors delivering 17.15 A/W responsivity, a PDCR of 2.8×10^3, a 2.8×10^{13} Jones detectivity and an external quantum efficiency of 83.2%; this radiation-tolerant pairing is promising for space applications

IWGO-TuP-21 Epitaxial Growth of κ(ε)-Ga2O3 Thin Films on 4H-SiC Substrates by Mist Chemical Vapor Deposition, *Taisei Oya,* ***Kazuyuki Uno****,* Wakayama University, Japan

Gallium oxide (Ga_2O_3) faces challenges in achieving stable p-type conductivity and possesses relatively low thermal conductivity. One promising strategy to overcome these limitations is heteroepitaxial growth on 4H-SiC, whose high thermal conductivity and p-type conductivity can compensate for the intrinsic weaknesses of Ga_2O_3. However, reports on Ga_2O_3 heteroepitaxy on 4H-SiC substrates remain limited [1-3]. In this study, epitaxial growth on 4H-SiC substrates was carried out using mist chemical vapor deposition (mist-CVD), resulting in the formation of κ (ε)-phase Ga_2O_3 thin films. The growth results are presented, and the potential of this heteroepitaxial system is discussed.

Ga_2O_3 films were grown by mist CVD using a mixed precursor solution of [$GaCl_3$]=0.02 M and[Hacac]=0.06 M. The 4H-SiC (0001) substrates were pretreated by SPM (H_2SO_4:H_2O_2=3:1) cleaning and subsequent 10% of HF etching to obtain surfaces with a bilayer step structure. We thenvaried the substrate temperature to identify the temperature range in which continuous Ga_2O_3thin films can be formed. In addition, we tracked how the growth mode of the crystal evolves with increasing film thickness.

Thin-film growth was not observed on the carbon face of 4H-SiC, and no film was obtained on4◦ off-axis substrates. In contrast, thin-film growth was confirmed on the Si face of 4H-SiC(0001)on-axis substrates. According to X-ray diffraction measurements, crystalline film growth started attemperatures above 550°C, whereas continuous thin-film formation was achieved at temperaturesabove 600°C.At a growth temperature of 600°C, a κ(ε)-phase film initially grew coherently on the substrate and was subsequently followed by the formation of a lattice-relaxed layer. At a film thickness of approximately 300 nm, the XRC FWHM decreased, indicating improved crystalline orientation. At a growth temperature of 700°C, the β phase initially grew coherently on the substrate, followed by the formation of the κ(ε) phase after lattice relaxation. When the film thickness reached approximately 300 nm, the XRC FWHM decreased, indicating improved crystalline orientation, like the behavior observed for films grown at 600°C.

The coherent growth of κ(ε)-Ga_2O_3 in ultrathin films with thicknesses of 20–30 nm suggests its potential application as a dielectric layer in MOSFETs. Furthermore, the improvement in crystalline orientation for films thicker than 300 nm indicates the feasibility of κ(ε)-Ga_2O_3 for vertical device applications.

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IWGO-TuP-22 Stability and Interlayer Formation at Epitaxial p-type Oxides/Ga_2O_3 Interfaces, ***Anna Sacchi****, Michelle Smeaton,* National Laboratory of the Rockies*; Shivashree Shivamade Gowda,* University of Virginia*; Krishna Acharya,* Colorado School of Mines*; Steven R. Spurgeon,* National Laboratory of the Rockies*; Patrick Hopkins,* University of Virginia*; Vladan Stevanovic,* Colorado School of Mines*; Brooks Tellekamp, Andriy Zakutayev,* National Laboratory of the Rockies

Ga_2O_3 interfaces with p-type oxides are relevant for heterojunction device applications in power electronics. Among these, NiO [1] and Cr_2O_3 [2] are considered the most promising. To date, most studies on Ga_2O_3 based heterojunctions have focused primarily on device optimization rather than on the fundamental understanding of interface dynamics and long-term stability. This work aims to provide a deeper understanding of NiO/Ga_2O_3 and Cr_2O_3/Ga_2O_3 interfaces. A detailed growth campaign for NiO and Cr_2O_3 has been conducted via pulsed laser deposition on Ga_2O_3 substrates with two different orientations, *i.e.*, (001), and (−201). X-ray diffraction evaluated material quality and epitaxial relationship, revealing two possible different orientations of the epilayers depending on the nominal out-of-plane substrate orientation, *i.e.*, (111) NiO and (001) Cr_2O_3 aligned to Ga_2O_3 (101) and(-201) when grown on (001) or (-201) oriented Ga_2O_3, respectively. The detected two-fold epitaxial relationship is explained in terms of equivalence of the oxygen and gallium sublattices for the (101) and (-201) Ga_2O_3 planes. This finding also provides a useful methodology to characterize epilayers on an asymmetric substrate. Transmission electron microscopy (TEM) further validates the XRD results and expands the investigation of interface stability, addressing the potential formation of interfacial layers [3] under thermal treatments that simulate long-term high-temperature operation. Finally, thermoreflectance measurements

were conducted to probe heat transport across the interfaces, examining the influence of substrate and epilayer orientation as well as the presence of any interfacial layers.

IWGO-TuP-23 Structural Properties of Sn-Doped β-Ga_2O_3 Thin Films Grown on Off-Axis Sapphire Substrates by Mist Chemical Vapor Deposition, ***Jae-Hyeok LIM***, *Yun-Ji SHIN, Tae-Yong Park, Seong-Min JEONG,* Korea Institute of Ceramic Engineering and Technology, Republic of Korea*; Chang-Mo KANG,* Pusan National University, Republic of Korea*; Si-Young BAE,* Pukyoung National University, Republic of Korea

β-Ga_2O_3 is an ultra-wide bandgap semiconductor that has attracted significant attention for next-generation power electronic devices. Heteroepitaxial growth on sapphire substrates is promising due to its cost-effectiveness and scalability; however, the severe lattice mismatch often leads to poor crystalline quality and phase instability. In this study, the effect of substrate off-axis angle on the structural properties of Sn-doped β-Ga_2O_3 thin films was systematically investigated.

β-Ga_2O_3 thin films (~1.5 μm) were grown on c-plane sapphire substrates using a mist CVD process. Both on-axis and 7° off-axis substrates were employed, and Sn doping concentrations (UID, 1%, and 4%) were varied to examine their influence on structural and optical properties. The films were characterized by HR-XRD, AFM, and UV–Vis spectroscopy.

The 7° off-axis substrate significantly improved crystalline quality, reducing the rocking-curve FWHM from 2600–3700 arcsec (on-axis) to ~1600–1700 arcsec. Although increasing Sn incorporation led to crystalline degradation, the off-axis films maintained β-phase stability even at 4% doping. In contrast, on-axis films exhibited phase instability, evidenced by the disappearance of β-phase peaks and the emergence of secondary phases, suggesting a phase transition. AFM analysis revealed improved surface uniformity for off-axis films, although local roughening appeared at higher doping levels. UV–Vis measurements revealed a gradual bandgap narrowing with increasing Sn concentration. Notably, on-axis films exhibited a more pronounced decrease (~4.42 eV), whereas off-axis films retained higher bandgap values (~4.69–4.77 eV), indicating reduced defect-induced band tailing.

These results demonstrate that off-axis substrates effectively enhance crystalline quality and suppress Sn-induced phase degradation, likely through step-flow growth and improved strain relaxation, providing a viable route for scalable growth of high-quality Sn-doped β-Ga_2O_3 on cost-effective sapphire substrates.

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IWGO-TuP-24 Enhanced Surface Engineering and Deep Mesa Etching in Vertical Ru-Si-O/β-Ga_2O_3 Schottky Diodes, ***Aleksandra Wojcicka,*** Lukasiewicz Research Network - Institute of Microelectronics and Photonics, Poland

Realizing gallium oxide potential in vertical Schottky barrier diodes (SBDs) requires precise anisotropic dry etching, which simultaneously introduce near-surface damage and defect states, making subsequent wet etching equally important for surface engineering, as both steps strongly affect device performance. Despite extensive studies on wet etching treatments for β-Ga_2O_3 Schottky contacts, no universally optimal surface preparation procedure has been established, since the results depends on crystal orientation and metallization scheme. This remains particularly relevant for amorphous Ru-Si-O Schottky contacts, as their high work function (5.6 eV) makes them attractive for high-power β-Ga_2O_3 devices.

In this work, to investigate the effect of post-etch wet surface treatment, five types of Schottky diode samples were prepared: non-etched, plasma-etched, and plasma-etched samples subsequently treated with 25%wt. TMAH, Piranha solution, or H_3PO_4 prior to Ru-Si-O/Au anode deposition on the surface of (001) β-Ga_2O_3 epilayers (n~1x10^{16} cm^{-3}, ~10 μm). Surface engineering by H_3PO_4 and TMAH resulted in effective Schottky barrier heights of Φ_B = 1.95 ± 0.02 eV and 1.99 ± 0.03 eV, respectively, while the ideality factors were n=1.07±0.01 and n=1.06±0.02. Moreover, the breakdown voltage increased from approximately 950 V to up to ~1600 V. Subsequently, the BCl_3/Ar RIE-ICP etching process was optimized by tuning the pressure (5–30 mTorr), table RF power (0–100 W), and Ar content (0–60%), with the constant ICP power fixed at 1200 W, temperature of 20 °C, and the total gas flow at 40 sccm. The etching tests were performed through a 200 nm thick Ni mask. The optimized conditions were then combined with the previously developed post-etch wet-treatment procedure to fabricate three vertical Schottky diodes with target mesa depths of 0.8, 1.2, and 1.6 μm. The optimized post-etch treatment and mesa-etching process enabled vertical Ru-Si-O/β-Ga_2O_3 Schottky diodes with breakdown voltages exceeding 2 kV.

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IWGO-TuP-27 Investigation of NiO/Ga_2O_3 Heterojunction PN Diodes by using HF Surface Treatment, ***Ray Hua Horng,*** National Yang Ming Chiao Tung University (NYCU), Taiwan

This study explores the potential of Ga_2O_3 for high-power electronic devices. To achieve this, we fabricated a lateral p-NiO/n-Ga_2O_3 heterojunction PN diode. The fabrication process is used by MOCVD to grow the n-type Ga_2O_3 on a sapphire, followed by sputtering to grow the p-type NiO. Material characterization was performed using XRD, SEM, and AFM. XRD results indicated good epitaxial quality of the β−Ga_2O_3, and the surface grain boundary morphology was analyzed using SEM and AFM. In this study, HF surface treatment was applied to remove dangling bonds and residual Cl from dry etching, thereby enhancing the device's breakdown voltage. The results show that the fabricated diode with HF surface treatment exhibits excellent on/off ratio of 5.1×10^6 and breakdown voltage of 1.96 kV. These findings confirm that the HF surface treatment is an effective method for fabricating high-quality Ga_2O_3 devices.

IWGO-TuP-28 Mechanism and Mitigation of Step-Bunching Instability in Homoepitaxial (100) β-Ga_2O_3 Thin Films, ***Ta-Shun Chou,*** *Saud Bin Anooz, Zbigniew Galazka, Jana Rehm, Arub Akhtar, Martin Albrecht, Andreas Fiedler, Andreas Popp,* Leibniz Institute for Crystal Growth, Germany

Step-bunching is a classical morphological instability observed in nearly all epitaxially grown material systems, typically serving as a source of structural defects. This phenomenon results in increased surface roughness that hinders the quality of electrical contacts and degrades physical properties, such as the mobility of a two-dimensional electron gas (2DEG). (100) β-Ga_2O_3,asa promising plane for large-scale wafer production (up to 6-8 inches), generally requires high offcut angles to achieve the desired step-flow morphology with low defect density. In this context, step-bunching serves as a critical instability that dictates the transition between a smooth, atomically flat surface (step flow growth) and a faceted or defective film.

In this study, we identified two distinct step-bunching morphologies occurring under conditions of high doping concentration and low Ga supersaturation. We propose separate formation mechanisms to explain these observations: the first is attributed to the local pinning effect of adsorbed dopants or impurities (type 1, Figure 1) [1], while the second is characterized as a 'terrace-loading instability.' (type 2, Figure 2). This instability arises independently of impurities as a direct consequence of intrinsic growth dynamics and the Ehrlich–Schwoebel (ES) barrier. It emerges specifically when supersaturation levels exceed the system's capacity to efficiently incorporate growth species into the steps. Based on these mechanisms, we developed a mitigation strategy that stabilizes step advancement by tuning the Ga supersaturation at the growing step front. This approach maintains the desired step-flow morphology across a wide doping range (10^{16} cm^{-3} to 10^{19} cm^{-3}) while preserving high carrier mobilities.

Figure 1. Step-bunching type 1, step-pinning type observed while doping above 10^{18} cm^{-3}.[1]

Figure 2. Step-bunching type 2, terrace-loading type observed due to an increase in local supersaturation.

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IWGO-TuP-29 α-Ga_2O_3 Thin Film Grown on Micropatterned Sapphire Substrate, ***Kotaro Etokoro,*** Kyoto University, Japan*; Takeru Wakamatsu, Yuki Isobe,* kyoto University, Japan*; Kentaro Kaneko,* Ritsumeikan university, Japan*; Katsuhisa Tanaka,* Kyoto University, Japan

α-Ga_2O_3 is one of the promising materials for power-switching devices because of its large bandgap of E_g = 5.3 eV [1]. Recently, high quality α-

Ga_2O_3 epilayers and heterostructures have been prepared on sapphire substrates. Due to the large in-plane lattice mismatch between the film and the substrate, however, α-Ga_2O_3 epilayers grown on sapphire substrates in general suffer from the formation of dislocations with a density of about 10^{10} cm^{-2} [2]. In this study, an attempt was made to grow α-Ga2O3 films with a reduced density of dislocations on sapphire substrates, for which lens-shaped micropatterns without hollow were fabricated before the film growth.

We fabricated micropatterns in which micro-cylinders (designed diameter was 2 μm) were arranged at different periods (designed center-to-center distances were 3, 4, and 6 μm) to construct a hexagonal lattice on the surface of sapphire substrate (10 x 10 mm^2 square, *c*-plane) by photolithography and dry-etching. We prepared α-Ga_2O_3 films on the patterned substrates using the mist-CVD process with the growth time of 30 to 300 min.α-Ga_2O_3 was grown on each cylinder with a shape of hexagonal truncated pyramid with the top being the *c*-plane (0001). For the case of the film grown for 300 min, the facet of *c*-plane was lost, and the pyramidal shape resulted. In contrast, for the film grown on the substrate patterned with a period of 3 and 4 μm, the surface of the film, which was the *c*-plane, became flat and uniform.

X-ray diffraction ω-rocking curve was obtained to examine the crystallinity of the films.We calculated the threading dislocation (TD) density from the full width at half maximum of the diffraction lines [3]. The total density of TD, including screw and edge dislocations, was an order of 10^{10} cm^{-2} for the film grown on the substrate without any patterns, while the TD density was reduced to 10^8 cm^{-2} when the patterned substrate was used.

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IWGO-TuP-30 Stabilization of Rutile GeO_2 on R- and M-Plane Al_2O_3 by Plasma-Assisted Molecular Beam Epitaxy*, Alexander Karg,* *Satjawoot Phiw-Ondee, Manuel Alonso-Orts, Martin Samuel Williams, Marco Schowalter, Andreas Rosenauer, Martin Eickhoff,* University of Bremen, Germany*; Patrick Vogt,* Paul-Drude-Institut für Festkörperelektronik Leibniz-Institut im Forschungsverbund Berlin, Germany

Rutile germanium dioxide (r-GeO_2), possessing a bandgap of approximately 4.6 eV [1], has recently emerged as a promising material among ultra-wide bandgap (UWBG) semiconductors for applications in high-power electronic devices. Compared to other UWBG oxide semiconductors such as β-Ga_2O_3, r-GeO_2 exhibits a significantly higher thermal conductivity. Furthermore, while Ga_2O_3 can only be doped n-type, both n- and p-type conductivity are predicted for r-GeO_2 [2], a very rare yet desirable property of UWBG semiconductors.

Regarding the epitaxial growth of r-GeO_2, only a limited number of reports exist. In this contribution we focus on molecular beam epitaxy (MBE), for which initial studies employed a graded buffer approach on r-TiO_2 or r-plane Al_2O_3 substrates. In contrast to these studies, we do not use either a pure GeO_2 or Ge source - instead, a powder mixture of both. This approach allows for the evaporation of GeO at significantly lower cell temperatures below 650°C while still achieving commonly used fluxes.

Concerning the layer sequence, we present an alternative concept to stabilize r-GeO_2: Following the growth of SnO_2 and $Ge_xSn_{1-x}O_2$ buffer layers on m-and r-plane Al_2O_3 substrates, controlled Sn-etching and GeO-exposure of the growth surface are used to enable nucleation of pure r-GeO_2. A comprehensive analysis of the growth parameter space is presented using high-resolution X-ray diffraction (XRD), atomic force microscopy, X-ray photoelectron spectroscopy and scanning transmission electron microscopy (STEM). The nucleation mechanism of GeO_2 is also discussed.

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IWGO-TuP-31 Deep-Etch Mesa Edge Termination for β-Ga_2O_3 Schottky Barrier Diodes*, Charlotte Conway,* *Aditya K Bhat, Sai Charan Vanjari,* University of Bristol, UK*; Jacob Mitchell, Jay Burnett, Kerry Roberts, Huma Ashraf,* KLA Corporation UK Ltd, UK*; Matthew Smith, Xiao Tang, Martin Kuball,* University of Bristol, UK

The full potential of vertical β-Ga_2O_3 Schottky Barrier Diodes (SBDs) is yet to be reached due to premature breakdown caused by electric field crowding at the Schottky contact edge. Efficient edge termination is essential to realise devices with near theoretical performance: providing higher breakdown voltages and greater efficiency than wide bandgap devices such as SiC [1]. This work explores the solution of deep mesa etching, reducing field crowding at the anode edge. While such edge termination has been realised in other materials [2,3], achieving deep etches in Ga_2O_3 has been challenging [4]. There is also disagreement whether optimal performance occurs in Ga_2O_3 when the trench reaches the full depth of the depletion layer [2], or if there is a shallower saturation depth [4].

This work demonstrates deep etch trenches in Ga_2O_3 in excess of 10μm depth for mesa edge termination, using a novel etch approach. The etch rate exceeds 400nm/min – over 8 times faster than standard methods. We have realised over 10μm deep etch and demonstrated it on a circular SBD. We determine optimal trench depth and placement to achieve the most favourable edge termination and thus enhanced electrical characteristics. The distance between trench and anode edge are varied and the electrical device performance compared. TCAD simulations show a deeper trench gives better electric field uniformity, with 10μm depth demonstrating superior field suppression. In simulation, there is little difference in electric field profile of mesa SBDs on a 5μm and 10μm epitaxial drift layer. This is tested experimentally by electrical testing of SBDs fabricated at different etch depths on 5μm and 10μm drift layers. The results deepen understanding of mesa edge termination, leading to its integration in more complex device designs, e.g. trench SBDs – potentially giving breakdown voltages higher than the 4kV previously demonstrated [5].

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IWGO-TuP-32 Plasma-Assisted MBE of β-Ga_2O_3/NiO Heterojunctions*, Andy Séguret,* Université Grenoble-Alpes, CEA, Grenoble INP, IRIG, PHELIQS, France*; Marty Volant,* Université Grenoble-Alpes, CEA, IRIG, MEM, France*; Fabien Jourdan,* Université Grenoble-Alpes, CEA, Grenoble INP, IRIG, PHELIQS, France*; Yann Genuist,* Université Grenoble-Alpes, CNRS, Grenoble INP, Institut Néel, France*; Hervé Roussel,* Université Grenoble Alpes, CNRS, Grenoble INP, LMGP, France*; Hanako Okuno,* Université Grenoble-Alpes, CEA, IRIG, MEM, France*; Eirini sarigiannidou,* Université Grenoble Alpes, CNRS, Grenoble INP, LMGP, France*; Vincent Consonni,* 2. Université Grenoble Alpes, CNRS, Grenoble INP, LMGP, France*; Eva Monroy, **Julien Bosch,*** Université Grenoble-Alpes, CEA, Grenoble INP, IRIG, PHELIQS, France

With the growing demand for power electronics, ultra-wide-bandgap materials such as diamond, AlN, and Ga_2O_3 are emerging as candidates to surpass the performance limits of SiC and GaN. Among them, β-Ga_2O_3 is particularly attractive due to its 4.9 eV bandgap and breakdown field exceeding 8 MV/cm, resulting in high power-device figures of merit. However, its low hole mobility[1] and unintentional n-type conductivity[2] necessitate an alternative p-type material for rectifying devices. NiO is well suited for this role, as it is naturally p-type, wide bandgap, and forms a staggered type-II heterojunction with Ga_2O_3. In this context, plasma-assisted molecular beam epitaxy (PAMBE) offers high purity, precise thickness control, low growth temperatures, and sharp interfaces, enabling the growth of low-defect and high-performance heterostructures.

Here, we report PAMBE growth of Ga_2O_3 on AlN templates on c-plane sapphire at temperatures between 580 and 780 °C. Although β-Ga_2O_3 has a monoclinic structure, its (−201) plane exhibits hexagonal symmetry with a reduced in-plane lattice mismatch to the (0001) III-nitride surface (~2.4% along [010]β-Ga_2O_3 ∥ [11-20]AlN [3]). In situ RHEED supports this epitaxial relationship and indicates lattice relaxation within the first few nanometers of growth.

We then demonstrate PAMBE growth of NiO on Al_2O_3 and (001) Ga_2O_3 substrates over a temperature range of 530–730 °C. Electron microscopy and atomic force microscopy reveal the deposition of an approximately 100 nm-thick NiO layer with a remarkably flat surface. X-ray diffraction

measurements show that the films adopt the (111) and (133) rocksalt NiO orientations on Al_2O_3 and Ga_2O_3 respectively, and confirm the epitaxial nature of the growth.

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IWGO-TuP-33 Long-Term Performance of Gallium Oxide-Based Hydrogen Sensors at 600˚C, ***William Callahan,*** National Laboratory of the Rockies*; Kingsley Egbo,* Headway Technologies*; Anna Sacchi, Davi Febba,* National Laboratory of the Rockies*; Anna Staerz, Ryan O'Hayre,* Colorado School of Mines*; Brooks Tellekamp, Andriy Zakutayev,* National Laboratory of the Rockies

Electronic devices capable of functioning at elevated temperatures are essential for enhancing efficiency and safety across a broad spectrum of applications, spanning industrial, transportation, and energy sectors. Such high-temperature environments are frequently coupled with additional challenging conditions, such as low-oxygen or strongly reducing atmospheres.

Among the most fundamental devices required for these environments are gas sensors, which can detect abrupt shifts in environmental conditions and warn of impending hazards. Identifying and evaluating gas sensor materials and stacks that can dependably function over extended periods under these demanding high-temperature conditions is a challenging yet critical component of device development.

In this presentation, I will outline our methodology for long-term characterization of high-temperature gallium oxide devices operating as hydrogen sensors in harsh conditions. I will cover the range of device architectures that were evaluated and detail the testing procedures that were employed, including our demonstration of 1,000 hours of continuous operation of a Pt/Cr_2O_3:Mg/Ga_2O_3 hydrogen sensor at 600°C.

IWGO-TuP-35 Band Alignment of NiO_x/β-Ga_2O_3(001) Heterojunction Consistently Determined by *I-V, C-V,* and IPE Measurements, ***Akihira Munakata,*** University of Tokyo, Japan*; Hironobu Miyamoto, Kohei Sasaki,* Novel Crystal Technology, Inc., Japan*; Takuya Maeda,* University of Tokyo, Japan

NiO_x/β-Ga_2O_3 heterojunction diodes (HJDs) are promising for high-power applications. However, their current transport mechanism and band alignment remain unclear [1–4]. In this work, the NiO_x/β-Ga_2O_3 HJDs are fabricated, and the current transport and the interface properties are investigated by capacitance-voltage (*C-V*), current-voltage (*I-V*), and internal photoemission (IPE) spectroscopy measurements.

The net donor concentration of the β-Ga_2O_3 epitaxial layer was 4.3×10^{16} cm^{-3}. From the *C-V* measurements, the built-in potential of 2.29 eV was obtained. The potential barrier height ($e\phi_{b,C\text{-}V}$) from the fermi level to the conduction band minimum of β-Ga_2O_3 at the interface was obtained as 2.41 eV. The forward *I-V* characteristics showed an ideality factor of 1.06, suggesting the thermionic emission (TE) and/or diffusion transport. Assuming that the recombination rate near the interface is high enough, the *I-V* characteristics were analyzed by the TE model, and the barrier height ($e\phi_{b,I\text{-}V}$) of 2.36 eV was extracted. Notably, $e\phi_{b,I\text{-}V}$ shows excellent agreement with $e\phi_{b,C\text{-}V}$. The photocurrent spectroscopy measurements were also performed. The photocurrent spectrum showed a clear linearity in the modified Fowler plot ($Y^{1/3}$ vs hv) [5, 6], resulting in the direct extraction of $e\phi_{b,IPE}$ as 2.44 eV. The band alignment of NiO_x/β-Ga_2O_3 was consistently obtained by *C-V*, *I-V* and IPE measurements. The reverse *I-V* characteristics of the HJD demonstrated a breakdown voltage of 1415 V (maximum parallel-plane breakdown field of 4.2 MV/cm). The leakage current under high reverse voltage may originate from the electron tunneling from the NiO_x valence band.

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IWGO-TuP-37 Deep-Acceptor-Mediated Inversion Enabling Normally-Off β-Ga_2O_3 MOSFETs without Epitaxy, *Sarit Dhar, Tamara Isaacs-Smith,* Auburn University*; Jacob Lawson, Charles Ebbing, Chase Kitzmiller, **J. Neil Merrett,*** Air Force Research Laboratory, USA

The absence of shallow p-type dopants in β-Ga_2O_3 limits realization of normally-off MOSFET architectures analogous to those used in Si and SiC power devices. In this work, enhancement-mode lateral field-effect transistors are demonstrated on Mg-compensated semi-insulating (010) β-Ga_2O_3 substrates without epitaxial regrowth. The devices exhibit threshold voltages exceeding 2.5 V and inversion-channel field-effect mobilities of ~45 $cm^2/V\cdot s$ at room temperature. Preliminary switching measurements indicate microsecond-scale turn-on and turn-off with nearly symmetric rise and fall times. The observed switching behavior is primarily limited by external parasitics, the device gate length and associated capacitances. Surface inversion arises from band-bending–induced ionization of deep Mg acceptors, enabling electron channel formation despite the absence of mobile holes. This mechanism differs fundamentally from conventional inversion in Si and SiC, where shallow acceptor doping provides a hole-rich p-body. In β-Ga_2O_3, the ultra-wide bandgap enables enhancement-mode operation through field-induced ionization of compensating deep acceptors. These results establish a new regime of transistor operation in ultra-wide-bandgap semiconductors governed by deep-level compensation and provide a pathway for monolithic integration of depletion- and enhancement-mode Ga_2O_3 power devices on semi-insulating substrates.Acknowledgement: This work was supported by the Auburn University RSP program and Air Force Research Laboratory. + Author for correspondence: sarit_dhar@auburn.edu

IWGO-TuP-40 Vertical Trench-Mos Barrier Diode on (001) β-Ga_2O_3 with Trench Formation by Hot H_3PO_4 Treatment, ***Aaron Adams,*** KBR/AFRL

β-Ga_2O_3 is poised as the semiconductor of the future for efficient power electronic devices due to the high predicted electric field strength and availability of shallow donors. However, the lack of p-type doping means a well-rectifying diode with low forward losses likely necessitates trench formation for sidewall junctions with RESURF effect to suppress leakage current [1]. To avoid performance penalties from bulk or interface states introduced during dry etching, it is desirable to find a damage free etch. Hot H_3PO_4 has highly anisotropic etch rates in β-Ga_2O_3 [2], making it a suitable candidate for a plasma-free trench formation process. This work demonstrates trench-MOS barrier diodes (TMBDs) fabricated with a wet-only trench etch.

Devices were fabricated on a ~11.3 µm, 2.5×10^{16} cm^{-3} Si-doped HVPE layer grown on n+ (001) substrate by Novel Crystal Technology. Trench structures were patterned with subtractively defined SiO_2 mask, with 2-4 µm SiO_2 stripes nominally aligned to [100]. The sample was submerged for 120 minutes in H_3PO_4 at 150 °C. SiO_2 was removed by BOE; 50 nm of Al_2O_3 was deposited by PEALD; Al_2O_3 vias were lithographically patterned and BCl_3 dry etched; finally, top-side anode and back-side cathode contacts were formed by patterned Pt/Au and blanket Ti/Au, respectively.

After wet etching, symmetric sidewalls (48°∠ (001)) appeared, nominally parallel to {035} planes. The etch stop on {035} could be due to high atomic density from coplanar Ga_I sites and coplanar O_I sites or octahedral Ga site bond geometry, with Ga_{II}-O_I and Ga_{II}-O_{II} bonds that are nearly in plane. The etch-resistant surface indicates a chemically stable surface suitable for critical device junctions. Etch depth was limited by the formation of the {035} facet; while the (001) field etched ~2 µm, the narrower trenches were shallower due to etch termination when {035} planes met to form a “V”.

DC I-V characteristics were measured at room temperature, and TMBDs of varying geometry were compared to a cofabricated planar Schottky diode. The TMBDs show slighty higher $R_{on,sp}$ than the SBD, from 2.5 to 3.9 $m\Omega\cdot cm^2$ due to the current choking of the fin structure. Conversely, the TMBDs with larger trench width (and thereby depth) showed greater leakage current reduction, with leakage largely in the noise and V_{bk} increased from 215 V to 1122 V. Due to the dry etch via, a small hysteresis of < 200 mV in the forward I-V was observed in all devices. TMBDs showed no additional hysteresis, indicating a high-quality interface suitable for trench-based device structures in β-Ga_2O_3.

IWGO-TuP-41 Challenges and Solutions in Mist-CVD of Ga_2O_3 Heteroepitaxial Films, ***Roman Yatskiv,*** Institute of Photonics and Electronics of the Czech Academy of Sciences, Czechia

Mist chemical vapor deposition (mist-CVD) has recently attracted interest as a facile, cost-effective, and environmentally friendly method for the deposition of Ga_2O_3 films [1]. We address selected challenges and issues that hinder the fabrication of high-quality Ga_2O_3 epitaxial films [2]. First,

based on numerical simulations of the gas flow (Fig. 1b), we demonstrated that the use of a fan to introduce atmospheric air into the horizontal growth reactor avoids the formation of vortices and mist velocity fluctuations, which develop when a conventional carrier-gas delivery system is employed. Second, we experimentally proved that when the thickness of Ga_2O_3 increases, a multiphase epitaxial film forms, presumably due to enhanced thermal stress (Fig 1c). Finally, we experimentally investigated the effects of growth temperature and precursor type on phase formation (Fig. 1d).

Figure 1 (a) Schematic of the mist-CVD system for the growth of Ga_2O_3; **(b)** temperature velocity and pressure fields in the mist-CVD reactor modelled using COMSOL; **(c)** schematic illustration of the critical thickness for processing at 550 °C; and **(d)** schematic illustration of theinfluence of the growth temperature and precursor type on phase formation.

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IWGO-TuP-42 Plasma-Assisted Surface Pretreatment of Sapphire Substrates for High-Performance β-Ga_2O_3Solar-Blind Photodetectors, ***An-Na Cha**, Gieop Lee,* Chonnam National University, Republic of Korea*; Sunjae Kim,* University of Oslo, Norway*; Dae-Woo Jeon, Ji-Hyeon Park,* Korea Institute of Ceramic Engineering and Technology, Republic of Korea*; Wan-Sik Hwang,* Korea Aerospace University, Republic of Korea*; Jun-Seok Ha,* Chonnam National University, Republic of Korea

Beta-gallium oxide (β-Ga_2O_3) is a premier ultra-wide bandgap semiconductor tailored for next-generation optoelectronics and solar-blind photodetectors. While sapphire offers a cost-effective and highly scalable platform for β-Ga_2O_3 heteroepitaxy, interfacial instability and non-uniform nucleation remain critical limitations for achieving reliable device performance.

In this study, we report a systematic investigation into the plasma-assisted surface pretreatment of sapphire substrates to optimize the interface for β-Ga_2O_3 photodetectors. Prior to epitaxial growth, substrates were subjected to distinct plasma chemistries to thoroughly examine their effects on surface modulation, structural integrity, and subsequent device characteristics. By elucidating the correlation between tailored surface conditions and the optoelectronic behavior of the fabricated devices, we clarify the fundamental role of plasma-assisted interface engineering.

Our findings demonstrate that optimized plasma pretreatment dramatically enhances both material quality and device performance. The optimized surface exhibited higher surface energy and a reduced surface roughness of 0.37 nm, leading to superior structural integrity with a narrowed X-ray diffraction (XRD) full width at half maximum (FWHM) of 43 arcsec and suppressed oxygen defects (25.3%). Consequently, photodetectors fabricated on these treated substrates exhibited a remarkable photo-to-dark current ratio (PDCR) of 10^5 and an exceptionally fast response time of 3.74 s, vastly outperforming untreated samples. This work establishes plasma-assisted surface pretreatment as a highly effective method for advancing the commercial viability of heteroepitaxial β-Ga_2O_3 optoelectronic devices.

IWGO-TuP-43 Effect of Thermal Treatment on the Heteroepitaxial Growth of Ga2O3 on Sapphire Substrates, ***Gieop Lee**, An-Na Cha, Sang Hyeon Ahn,* Chonnam National University, Republic of Korea*; Sung Jin Son, Young-Boo Moon, Myung Sik Kim,* UJL Inc., Republic of Korea*; Moo Sung Lee, Jun-Seok Ha,* Chonnam National University, Republic of Korea

Gallium oxide (Ga_2O_3) is a promising ultra-wide bandgap semiconductor for next-generation power electronic devices due to its high breakdown field and excellent material properties. However, the high cost and limited availability of native Ga_2O_3 substrates have driven the development of heteroepitaxial growth on cost-effective substrates such as sapphire. In this context, thermal treatment has emerged as an effective approach to control surface morphology and crystalline quality.

In this study, the effects of thermal treatment on the heteroepitaxial growth of Ga_2O_3 on sapphire substrates were systematically investigated through independent pre- and post-thermal processes. For the pre-thermal treatment, sapphire substrates were annealed prior to growth, leading to the formation of terrace-like surface structures. Subsequent Ga_2O_3 films were grown by metal-organic chemical vapor deposition (MOCVD) to evaluate the influence of surface modification on epitaxial growth behavior.

In a separate experiment, post-thermal treatment was applied after Ga_2O_3 growth to examine its impact on phase stability, crystallinity, and surface properties. The results indicate that thermal treatment significantly affects the structural properties of the Ga_2O_3 films. In particular, Al diffusion from the sapphire substrate into the Ga_2O_3 layer was observed after thermal treatment, resulting in bandgap modification of the films.

IWGO-TuP-44 Area-Dependent Effects on the Breakdown Voltage of β-Ga_2O_3 Schottky Barrier Diodes for Scaling to High-Absolute Currents, ***Wolfgang Buchmaier**,* Univeristy of California, Santa Barbara*; Steve Rebollo, Yizheng Liu, Sriram Krishnamoorthy, James Speck,* University of California at Santa Barbara

β-Ga_2O_3 is a promising material for use in power electronic devices because of its ability to be melt-grown into large area substrates, which are required for the high current requirements for power electronic devices. Large areas, however, increase the potential of including a substrate defect or epitaxial drift layer defects within the footprint of the device. These defects can increase leakage current, reduce breakdown voltage, and potentially limit the scalability of β-Ga_2O_3 power electronic devices. This study demonstrates planar, field-plated, Schottky barrier diodes with diameters ranging from 88 µm to 1.4 mm, and a minimal decrease in the breakdown voltages with increasing device area. We have employed a novel ALD mid-κ dielectric (ZrO_2) field plate in this work.

Devices were fabricated on 10 µm Halide Vapor Phase Epitaxy (HVPE)-grown (001) oriented drift layer from Novel Crystal Technology. First a backside Ti/Au contact was deposited using electron beam evaporation. Next, Ni (30 nm) / Au (5 nm) Schottky contacts were deposited using and to protect the epitaxial layer from ion-damage. Next a 200 nm layer of the mid-κ dielectric ZrO_2 was blanket deposited using only atomic layer deposition, which was etched using reactive ion etching for the anode contact formation. This dielectric serves as a robust edge-termination method to reduce electric field concentration, in order to ensure the quality of the epitaxial layer is being measured with the breakdown measurements. This is the first report of a fully ALD-grown thick ZrO_2 field plate oxide in β-Ga_2O_3, which should result in elimination of potential interfacial charge from a mixed process. Lastly a Ni/Au layer was deposited to create the field plate extension of 10 µm.

Next, current-voltage and capacitance-voltage measurements were performed. The devices exhibit rectifying behavior with ideality factor of 1.0, specific-on resistance of ~10 Ωcm^{-2}. Capacitance voltage measurements confirm the net-doping concentration for the epitaxial layer to be N_A-N_D=1e-16 cm^{-3}, and a built-in voltage of 1.1 V.

High voltage breakdown measurements were then performed, in order to determine how to breakdown characteristics differ with the scaling of device area. Catastrophic breakdown was not observed in the voltage range used for the measurement. We define breakdown voltage criterion as the reverse bias at which the reverse leakage current is 1 mA/cm^2. Statistical analysis shows that the breakdown voltage decreases by 97 V per 10-fold increase in device area, and the large area devices maintained impressive reverse leakage performance, indicating robust edge termination and high quality of the epitaxial layer.

IWGO-TuP-45 Nitrogen-Doped Epitaxial Structures Towards Scalable Enhancement Mode Vertical Devices, ***Rachel Kahler**, Carl Peterson, Yizheng Liu, Chinmoy Nath Saha, Steve Rebollo, Jim Speck, Sriram Krishnamoorthy,* University of California, Santa Barbara

The ability to create enhancement mode devices with larger trench or fin dimension allows for scalable and manufacturable fabrication of Ga_2O_3 power devices. Larger fins are enabled by including an insulating deep acceptor doped layer in the device between the drift layer and n+ source contact. Growing this structure epitaxially eliminates the need for ion implant to develop the insulating layer. We report on β-Ga_2O_3 deep acceptor/n- junctions that include a nitrogen-doped layer grown in-situ using metalorganic chemical vapor deposition (MOCVD). Growth was performed using TEGa, pure O_2 (5N), silane as the dopant source, Ar as carrier gas, and 50 ppm dilute ammonia (NH_3) in N_2 as the nitrogen dopant source (henceforth referred to as NH_3/N_2) in an Agnitron Agilis MOCVD reactor. The junction was grown on Sn-doped (010) substrates from Novel Crystal Technologies. The structure consisted of a 2 µm intentionally 5 x 10^{15} cm^{-3} doped n- layer, followed by a 100 nm N-doped layer with a flow of 1500 sccm NH_3/N_2 with an N concentration of ~1.7 x 10^{19} $atoms/cm^3$. The

sample was fabricated into Schottky diodes with Ni/Au/Ni contacts and mesa isolated into the n- drift layer using a BCl_3 inductively coupled plasma (ICP) etch. Capacitance-voltage (C-V) measurements gave a built-in potential (V_{bi}) of 3 V. A maximum breakdown of 231 V was achieved for the 100 nm N doped structure. After characterizing the deep acceptor/n- junctions, a structure with an n- drift layer, deep acceptor layer, and n+ source layer was grown. The n-/deep acceptor/n+ structure comprised of a 5 µm thick intentionally 1 x 10^{16} cm^{-3} doped n- layer, 300 nm deep acceptor layer with 1500 sccm of NH_3/N_2, and a 300 nm n+ layer with an intended doping of 2 x 10^{19} cm^{-3}. CTLMs and vertical diodes were fabricated to ensure Ohmic contact to the n+ layer and to characterize the breakdown and leakage of the structure. The diodes were mesa isolated to the n- layer using an ICP etch. CTLM measurements showed Ohmic behavior, with a sheet resistance of 42.77 Ω/□ and contact resistance of 0.93 Ω-mm. Vertical leakage data shows low current density in forward bias, highlighting the current blocking capability of the N doped layer. Maximum reverse breakdown for 50 µm diodes was 758 V. This study shows the promise of epitaxially grown deep acceptor/n- junctions in β-Ga_2O_3 to enable scalable and manufacturable enhancement mode power devices.

IWGO-TuP-46 Identification of Facets Formed on (011) β-Ga_2O_3 Homoepitaxial Layers, ***Yuichi Oshima***, *Takayoshi Oshima,* National Institute for Materials Science, Japan

β-Ga_2O_3 is a promising power semiconductor for next-generation high-power devices because of its high breakdown electric field and the availability of large-area bulk substrates. For vertical devices, thick, high-purity drift layers are required, and halide vapor phase epitaxy (HVPE) is one of the most suitable growth techniques owing to its high growth rate and low impurity incorporation. Although (001)-oriented substrates have commonly been used for HVPE homoepitaxy, the resulting surfaces often contain pits or grooves originating from substrate defects and usually require extensive chemical mechanical polishing before device fabrication. Recently, the (011) orientation has attracted attention because it enables groove-free growth and suppresses chlorine incorporation during HVPE [1,2]. However, its detailed surface morphology has not been fully clarified.

Here, we investigated a 3.6-µm-thick β-Ga_2O_3 homoepitaxial layer grown on a (011) substrate by HCl-based HVPE [2]. Scanning electron microscopy (SEM) revealed that the surface consisted of macrosteps and terraces elongated along the [1−11] direction. Based on atomic force microscopy (AFM) and transmission electron microscopy (TEM) observations, the macrosteps and terraces were identified as the (110) and (−134) facets, respectively. The experimentally determined surface coverage ratio of these facets was 0.210:0.790, in good agreement with the geometrically expected ratio of 0.219:0.781 calculated from the orientation relationship among the (011), (110), and (−134) planes.

These results show that the nominally (011)-oriented HVPE-grown β-Ga_2O_3 surface is actually composed of (110) macrosteps and (−134) terraces. Thus, growth kinetics and impurity incorporation should be discussed based on the actual faceted morphology. This finding provides important insight into the growth behavior of (011) β-Ga_2O_3 homoepitaxial layers.

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IWGO-TuP-47 Self-Exfoliated *α*-Ga_2O_3 Flakes for Vertical Electronic and Optoelectronic Devices, ***Sunjae Kim***, University of Oslo, Norway*; Wan Sik Hwang,* Korea Aerospace University, Republic of Korea*; Dae-woo Jeon,* Korea Institute of Ceramic Engineering and Technology, Republic of Korea*; Andrej Kuznetsov,* University of Oslo, Norway*; Ji-Hyeon Park,* Korea Institute of Ceramic Engineering and Technology, Republic of Korea

Gallium oxide (Ga_2O_3) has attracted considerable attention as an ultra-wide bandgap semiconductor for next-generation power electronic and solar-blind optoelectronic devices. Among the Ga_2O_3 polymorphs, *α*-Ga_2O_3 has the widest bandgap and can be hetero-epitaxially grown on sapphire substrates because of its relatively low lattice mismatch. However, the absence of a natural cleavage plane makes it difficult to obtain freestanding *α*-Ga_2O_3 layers using conventional mechanical exfoliation, limiting the development of substrate-independent vertical device structures. Although self-exfoliation of thick *α*-Ga_2O_3 layers on sapphire has been reported, the exfoliation behavior has not been systematically investigated.In this study, thick *α*-Ga_2O_3 epitaxial layers were grown on sapphire substrates by hydride vapor phase epitaxy (HVPE). The exfoliation behavior was systematically investigated to understand the exfoliation mechanism and increase the lateral flake size of *α*-Ga_2O_3. The exfoliated flakes were used to fabricate vertical schottky barrier diodes (SBDs) and UV photodetectors, and the electrical and optoelectronic characteristics of the devices were evaluated. These results improve the understanding of the self-exfoliation process in *α*-Ga_2O_3 and demonstrate the potential of self-exfoliated *α*-Ga_2O_3 flakes for various electronic and optoelectronic device applications.

IWGO-TuP-48 Simulation of Amorphous Aluminum Gallium Oxide (Ago) Films for Memristor Devices, ***Joshua Stoner***, *Michael Mitchell, Shweta Joshi,* The George Washington University*; Olaf Vant 'T Erve,* Naval Research Laboratory*; Daniel Gopman,* NIST*; Gina Adam,* The George Washington University

Amorphous aluminum gallium oxide (AGO) is being investigated as a potential material for oxide-based memristive devices due to its tunable material properties, expected thermal stability, and the role oxygen vacancies are expected to play in resistive switching. However, correlating the deposition parameters with the memristor behavior is challenging and would require significant experimental developments. Complementary simulations would speed up the research in this area. As an initial step toward developing AGO memristor simulations, this work focuses on building small-scale atomistic models of both crystalline and amorphous AGO. Starting from crystalline oxide structures, computational methods are being used to generate amorphous configurations through structural relaxation, while also developing the simulation workflows needed to perform these calculations on high-performance computing resources. Current efforts have primarily focused on generating input structures, geometry optimization, and verifying that the resulting atomic configurations produce physically reasonable bonding environments.

These models provide an important first step toward understanding the local atomic environments present in amorphous AGO, which serves as the starting point for oxygen vacancy calculations and defect analysis.

These atomistic models will eventually be used to investigate oxygen vacancy formation, defect migration, conductive filament formation, and other mechanisms that contribute to resistive switching behavior in AGO-based memristive devices.

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