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Room Concourse - Session IWGO-TuP

IWGO Poster Session II

Moderator: Nidhin Kurian Kalarickal, Arizona State University

IWGO-TuP-1 Observation of the 2 eV Defect in Nitrogen Doped Ga_2O_3 by DLTS, *Jian Li,* Core4ce LLC*; Brenton Noesges, Prescott Evans,* Air Force Research Laboratory, Materials and Manufacturing Directorate, USA*; Jacob Breakfield, Zach Weber, Nolan Hendricks, Andy Green,* Air Force Research Laboratory*; Adam Neal, Tadj Asel,* ***Shin Mou,*** Air Force Research Laboratory, Materials and Manufacturing Directorate, USA

We demonstrate that the deep-level transient spectroscopy (DLTS) technique (conventional capacitance mode, samples in the dark) can routinely detect and characterize defects with activation energies >1 eV under judiciously selected experimental conditions in the temperature-rate space. Our DLTS results (Figure 1) are comparable to previous work [1], where the ~2.0 eV defect in nitrogen-implanted *b*-Ga_2O_3 was observed only by deep-level optical spectroscopy (DLOS) but not by DLTS of which conditions were less tuned towards detecting large activation energies. This augmented DLTS capability could enable full-bandgap defect study of general wide-bandgap semiconductors (e.g., GaN and SiC with E_g~3.3 eV) and is particularly relevant to understanding the effects of compensating acceptors in *b*-Ga_2O_3, whose activation energies are often large.

We apply this DLTS capability to investigate various species and preparation methods of compensating acceptors in *b*-Ga_2O_3 (e.g., N and Fe, ion implantation with various annealing conditions vs *in situ* doping) which are necessary for the optimization of semi-insulating substrates, buffers, and blocking layers critical to device behaviors such as breakdown, dynamics, and dispersion.

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-3 Temperature Dependent Switching Characteristics of p-Nio/β-Ga_2O_3 Heterojunction Mosfets Under Cryogenic Conditions, ***Joonhui Park***, *Taejun Park, Yusup Jung, Taiyoung Kang, Sinsu Kyoung,* PowerCubeSemi. Inc., Republic of Korea

The development of power semiconductor devices capable of reliable operation under cryogenic conditions is increasingly important for extreme-environment applications such as deep-space electronics, cryogenic sensing, and quantum technologies. β-Ga_2O_3, with its ultra-wide bandgap (~4.8 eV) and high critical electric field (~8MV/cm), has emerged as a promising material for next-generation high-voltage power electronics. However, the switching characteristics of β-Ga_2O_3-based transistors under cryogenic conditions remain insufficiently understood.

In this work, a β-Ga_2O_3 heterojunction field-effect transistor (HJ-FET) incorporating a p-type NiO gate layer was fabricated to form a p–n heterojunction on an n-type β-Ga_2O_3 channel. Temperature-dependent electrical characteristics were systematically investigated from room temperature to cryogenic temperatures (~–160 °C). As temperature decreased, the drain current gradually decreased and the threshold voltage shifted positively due to carrier freeze-out in the β-Ga_2O_3 channel. Meanwhile, the subthreshold slope improved from 224 mV/dec at room temperature to approximately 100–117 mV/dec under cryogenic conditions, accompanied by a significant enhancement in the on/off current ratio from ~10^5 to ~10^9. Despite the presence of gate leakage at low temperatures, the device maintained clear switching behavior with stable gate modulation.

These results demonstrate the feasibility of β-Ga_2O_3 heterojunction MOSFETs operating under cryogenic environments and provide insight into the low-temperature switching behavior of β-Ga_2O_3 power devices for extreme-environment electronic applications

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·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:

$I=\theta\cdot(9\pi/4)\cdot\varepsilon_s\cdot\mu\cdot d_{ch}\cdot(V^2/[F\cdot r_0^2])$

(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°C[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°C 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°C, but it significantly increased at T_{anneal}=700°C. 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°C, but it also significantly increased at T_{anneal}=700°C.Seebeck effect measurements showed p-type conductivity for all the films. The results brought us to determine heat-resistance temperature being around 600°C. The heat-resistance of the NiO thin film was improved through Li doping.

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IWGO-TuP-13 Heavy-Ion Microprobe Induced Parasitic Channel in Ga2O3 MOSFETs, ***Adam Neal,*** Air Force Research Laboratory, Materials and Manufacturing Directorate, USA*; Daram Ramdin,* Core4ce*; Eric O'Quinn,* University of Tennessee Knoxville*; Adam Charnas,* Air Force Research Laboratory, Materials and Manufacturing Directorate, USA*; Kay-Obbe Voss,* GSI Helmholtzzentrum für Schwerionenforschung, Germany*; Cale Overstreet,* University of Tennessee Knoxville*; Cameron Gorsak, Hari Nair,* Cornell University*; Andrew Green,* Air Force Research Laboratory, Sensors Directorate*; Thaddeus Asel, Shin Mou,* Air Force Research Laboratory, Materials and Manufacturing Directorate, USA*; Maik Lang,* University of Tennessee Knoxville

The development of the first ultrawide-bandgap β-Ga_2O_3 transistor in 2012has spurred intensive research into material properties and device optimization for the development of advanced electronics. Space applications of β-Ga_2O_3 are of particular interest due to the established susceptibility of Si, SiC and GaN to single event-burnout effects due to heavy ion collisions. Experiments elucidating the effects of heavy-ion

irradiation on β-Ga_2O_3 transistors are just beginning to be reported, and such studies are critical to inform the design and implementation of Ga_2O_3 power switches and amplifiers in space. In this study, 192 MeV ^{40}Ar and 1182 MeV Au species were used to perform spatially resolved "microprobe" characterization of Ga_2O_3 MOSFETs.Single ions are shot into the device with a lateral spatial resolution of ~0.5 micron by 0.5 micron, together with in-situ electrical characterization, to map the most sensitive regions of the device. We find that these lateral Ga_2O_3 MOSFETs do not suffer catastrophic single event burnout up to average electric fields of at least 0.66 MV/cm for 192 MeV ^{40}Ar or 0.05 MV/cm for 1182 MeV Au, but they experience significant threshold voltage shifts due to accumulated micro-dosing effects when the heavy ions impact the channel region. Analysis of I-V curves indicates a radiation-induced activation of the parasitic channel at the substrate-epi interface in these Ga_2O_3 devices causing significant negative threshold voltage shifts, where the parasitic channel was otherwise well controlled through appropriate surface treatment prior to epitaxial growth.This study points to the need for additional buffer engineering to mitigate parasitic channel formation at the substrate-epi interface for rad-hard Ga_2O_3 transistors.

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**, Young Min 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**, Young Min 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 ($\bar{2}01$) 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 ($\bar{2}01$) 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-19 Suboxide-MBE Growth of β-Ga_2O_3 on Metallic Ru(001)*, **Martin Samuel Williams**, Marco Schowalter, Aman Baunthiyal, Alexander Karg, Sushma Raghuvansy, Jens Falta, Andreas Rosenauer, Martin Eickhoff, Manuel Alonso-Orts,* Universität Bremen, Germany

The use of backside (BS) contacts for power distribution (BSPD) and even signal routing is gaining attention in physical design optimisation for its capacity to improve performance and power efficiency, while reducing cell height – presenting future routes for continued scaling of integrated circuits at smaller nodes [1]. BSPD and BS signal routing have enabled the implementation of 4-track standard-cell libraries, resulting in up to a 15% power reduction and a 35% area reduction compared to a 6-track library with BSPD only [2]. When combined with the ultra-wide bandgap of monoclinic β-Ga_2O_3, and consequently its high breakdown field, this approach presents an avenue for future efficient high-power devices.

Molecular beam epitaxy (MBE) enables the growth of crystalline β-Ga_2O_3 on substrates such as sapphire. However, it entails complex two-step growth kinetics – exhibited by the formation and desorption of the volatile Ga_2O suboxide in Ga-rich conditions – and low growth rates. Alternatively, suboxide MBE (S-MBE) simplifies growth of β-Ga_2O_3 to a single step, enabling more stable and higher growth rates in the suboxide-rich adsorption-controlled regime. Furthermore, S-MBE allows for epitaxial growth at lower temperatures – facilitating the growth of β-Ga_2O_3 on Ru while minimising oxidation of the metallic surface.

The growth of β-Ga_2O_3 on RF-sputtered Ru [3] is studied across a wide stoichiometry range, from $\varphi_{Ga2O}/\varphi_O = 0.05$ to $\varphi_{Ga2O}/\varphi_O = 10$, with nucleation in suboxide-rich growth aided by the inclusion of an initial buffer layer in stoichiometric growth conditions. (-201)-oriented β-Ga_2O_3 is observed to form across the investigated parameter space. The vertical conductivity of unintentionally and intentionally Si-, Sn- and Ge-doped films is studied, utilising the Ru film as a BS contact. Finally, Ru is demonstrated as a replacement for a lower distributed Bragg reflector in vertical optical cavities, exhibiting an as-deposited reflectance surpassing 70% over the near-UV and visible spectral range.

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IWGO-TuP-20 Gd Incorporation in β-Ga_2O_3 Grown by Suboxide MBE: Towards Ultraviolet Emission and Luminescent Thermometry*, Martin Samuel Williams, Marco Schowalter, Alexander Karg, Mahmoud Elhajhasan,* University of Bremen, Germany*; Marcus Rohnke,* University of Giessen, Germany*; Carsten Ronning,* University of Jena, Germany*; Gordon Callsen, Andreas Rosenauer, Martin Eickhoff,* ***Manuel Alonso-Orts****,* University of Bremen, Germany

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

Our recent work [2] studied Gd implantation in β-Ga_2O_3 thin films grown by atomic layer deposition (ALD) and molecular beam epitaxy (MBE). Detailed photoluminescence (PL) spectroscopy revealed a well-resolved manifold of four lines in the UV-B originating from the electronic transitions from the Stark splitting of the $^6P_{7/2}$ excited state to the $^8S_{7/2}$ ground level of Gd^{3+}. These results indicated that the transition energies in implanted β-Ga_2O_3:Gd films are largely independent of the growth method (for the undoped β-Ga_2O_3 films) and of the annealing conditions in the Gd-implanted layers, reflecting the weak sensitivity of the 4f electronic states to such small variations in the host crystal environment

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

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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 550ºC, whereas continuous thin-film formation was achieved at temperaturesabove 600ºC.At a growth temperature of 600ºC, 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 700ºC, 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 600ºC.

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.

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-25 Effect of Oxygen Ambient During Cool-Down on Nio/Ga_2O_3 Heterojunction Diodes*, **Ai Ho**, Cheng-Han Li, Ray-Hua Horng,* National Yang Ming Chiao Tung University (NYCU), Taiwan*; Ying-Hao Chu,* National Tsing Hua University, Taiwan

Gallium oxide (Ga_2O_3) has recently attracted significant attention as an ultra-wide bandgap semiconductor due to its large bandgap (4.7 - 4.9 eV) and high critical breakdown electric field (8 MV/cm), which enable a Baliga figure of merit (BFOM) as high as 3444. However, achieving p-type Ga_2O_3 remains a major challenge because of the difficulty in incorporating acceptor dopants and the limited generation and transport of holes. Furthermore, the relatively flat valence band structure leads to a large hole effective mass, resulting in low hole mobility.To address this issue, nickel oxide (NiO) has been widely used to form heterojunctions with Ga_2O_3, demonstrating a feasible approach in previous studies. In this work, we further investigate the impact of oxygen introduction during the cool-down process following metal-organic chemical vapor deposition (MOCVD) growth of Ga_2O_3. The differences between samples with and without oxygen introduction are systematically analyzed through electrical characterization. Overall, oxygen introduction enhances device breakdown characteristics and switching performance, which is further supported by material analysis using X-ray photoelectron spectroscopy (XPS).

IWGO-TuP-26 Sn-Induced Defect Engineering in β-Ga_2O_3: A Combined Experimental and First-Principles Study*, **Vijay Kumar Gudelli**,* King Abdullah University of Science and Technology, India*; Andres E Castano Hurtado,* King Abdullah University of Science and Technology (KAUST), Colombia*; Kishor Upadhyaya,* King Abdullah University of Science and Technology (KAUST), India*; Iman S Roqan,* King Abdullah University of Science and Technology, Saudi Arabia

β-Ga_2O_3, an ultrawide-bandgap semiconductor with a very high critical electric field, has strong potential for high-power electronic and optoelectronic devices but requires precise defect engineering to realize its full capabilities. This study presents a combined theoretical–experimental framework for understanding substitutional doping via Sn incorporation in epitaxial β-Ga_2O_3, clarifying the charge-compensation mechanisms and the associated optical signatures. Using advanced computational workflows that couple the ShakenBreak toolkit [1] for robust defect relaxation across charge states with the doped code for thermodynamic stability analysis, we systematically map Sn incorporation at the crystallographically distinct GaI (tetrahedral) and GaII (octahedral) sites. Density functional theory shows that the octahedral Sn_GaII configuration has markedly lower formation energies (by ~0.5–1 eV relative to tetrahedral Sn_GaI across relevant Fermi

levels and chemical potentials), leading to site-selective doping that tunes shallow donor levels near the conduction-band minimum and deep optical centres. These results are then used as input to DefectPL [2] for configuration-coordinate modelling of photoluminescence (PL) and photoluminescence excitation (PLE) spectra, enabling quantitative predictions of zero-phonon lines, phonon sidebands, and vibronic line shapes without empirical fitting. The calculated PL features are similar to our experimental measurements. By combining automated defect discovery, construction of formation-energy diagrams, and spectroscopic simulation, this work resolves site-specific doping behaviour in β-Ga_2O_3, addresses key gaps in defect thermodynamics, and outlines guidelines for designing materials for extreme-environment applications that require coupled electrical and optical control.

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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.

This work was supported by MIC under a grant entitled "R&D of ICT Priority Technology (JPMI00316): Next-Generation 14 Energy-Efficient Semiconductor Development and Demonstration Project (in collaboration with MOEJ)."

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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 600C*, **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-34 Investigation of the Effect of Heated-H_3Po_4 on Fin Sidewall Roughness and Electrical Performance*, **Xin Zhai**,* University of Michigan, Ann Arbor*; Jay Burnett, Kerry Roberts,* KLA-Tencor, UK*; Edward Walsby,* KLA-Tencor*; Huma Ashraf,* KLA-Tencor, UK*; Rebecca Peterson,* University of Michigan, Ann Arbor*; Elaheh Ahmadi,* University of California Santa Barbara

Vertical β-Ga_2O_3 trench diodes and FinFETs have attracted considerable interest for power-switching applications because they offer several advantages, including the no requirement for p-type doping, compatibility with enhancement-mode operation, and the potential to increase breakdown voltage without enlarging device area. These device concepts typically rely on high quality fin sidewall surface. In this work, we investigate the effect of post-etch treatment (PET) after chlorine-based dry etching of β-Ga_2O_3 focusing on how heated-H_3PO_4 influence the resulting profiles and sidewall roughness [1]. Under optimized etch conditions, we further assess the quality of the fin sidewall roughness through capacitance-voltage (C-V) characterization.**Fig. 1** compared the Ga_2O_3 fin sidewall morphology before and after hot phosphoric-acid PET for 20mins at 120 °C. **Fig. 1 (a)** and **(b)** show dry-etched fins without any subsequent smoothing, with fins oriented along [010] in **(a)** and [100] in **(b)**. Following the heated-H_3PO_4 treatment, the [010] aligned fin in **Fig. 1(c)** displays a smoother and more uniform sidewall compared with **Fig. 1(a)**, indicating that hot phosphoric acid serves as an effective chemical polishing step for this orientation without appreciable Ga_2O_3 consumption. This improvement is consistent with the electrical data in **Fig. 2**, where the treated sample exhibits a higher accumulation capacitance, whereas the untreated sample shows signatures of Fermi-level pinning. In contrast, for the [100] aligned fin, the post-treated sidewall in **Fig. 1(d)** appears similar roughness with the corresponding untreated case in **Fig. 1(b)**, suggesting that the same treatment is less advantageous for the [100] orientation.

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 $NiO_x/\beta\text{-}Ga_2O_3$ 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 $\beta\text{-}Ga_2O_3$ 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 $\beta\text{-}Ga_2O_3$ 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 $NiO_x/\beta\text{-}Ga_2O_3$ 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-36 Aln Mesa Sidewall Passivation Enables Thermally Stable Reverse Blocking in Vertical β-Ga₂O₃ Power Diodes*, **Ganesh Mainali**, Nuzhat Yousf,* King Abdullah University Of Science and Technology, Saudi Arabia*; Dhanu Chettri, Haicheng Cao, Leo Raj Solay,* King Abdullah University Of Science, Saudi Arabia*; Xiaohang Li,* King Abdullah University Of Science and Technology, Saudi Arabia

Ultra-wide-bandgap $\beta\text{-}Ga_2O_3$ has emerged as a leading candidate for next-generation high-voltage power electronics due to its large bandgap (~4.8 eV) and high critical electric field (~8 $MV\cdot cm^{-1}$). However, the performance of vertical $\beta\text{-}Ga_2O_3$ Schottky barrier diodes (SBDs) remains fundamentally limited by surface- and edge-related leakage arising from mesa isolation, particularly under high electric field and elevated temperature conditions.

In this work, we demonstrate AlN mesa sidewall passivation as an effective strategy to suppress reverse leakage and enhance electrothermal stability in vertical $\beta\text{-}Ga_2O_3$ SBDs. The AlN-passivated devices exhibit unchanged forward transport, maintaining thermionic-emission-dominated conduction with a peak current density of ~148 Acm^{-2} and a specific on-resistance of ~10 $m\Omega cm^2$, comparable to unpassivated devices. In contrast, reverse characteristics show orders-of-magnitude reduction in leakage current, with breakdown voltage improving from 586–681 V to 1.19–1.34 kV (refer Fig. 2 (b)).

Temperature-dependent measurements (25 °C – 400 °C) reveal a pronounced difference in leakage mechanisms (refer Fig. 2 (c) and (d)). The unpassivated diode exhibits strong thermally activated leakage with an activation energy of ~1.4 eV, consistent with barrier modulation and surface-assisted conduction (refer Fig. 3 (a)). In contrast, the AlN-passivated device demonstrates near temperature-independent reverse leakage, indicating effective suppression of surface states and stabilization of the Schottky barrier at the mesa edge.

Electrothermal TCAD simulations further show that AlN passivation reduces peak localized Joule heating at the mesa edge by ~25%, from ~68×10^6 to ~51×10^6 $W\cdot cm^{-3}$, while redistributing heat into the bulk drift region (refer Fig. 3(b) and (c)). This reduction in electrothermal feedback directly correlates with the observed suppression of leakage and enhanced breakdown stability.

The improvement is attributed to the combined effects of: surface state passivation, electric field redistribution at the mesa perimeter, enhanced thermal conduction at the sidewall interface. Unlike multi-layer dielectric field-plate approaches, this work demonstrates that a single conformal AlN layer is sufficient to achieve substantial improvements in both electrical and thermal performance.These results establish mesa sidewall electrostatic engineering using AlN as a scalable and effective pathway toward high-voltage, high-temperature $\beta\text{-}Ga_2O_3$ power devices for next-generation energy conversion systems.

IWGO-TuP-37 Deep-Acceptor-Mediated Inversion Enabling Normally-Off β-Ga₂O₃ MOSFETs without Epitaxy*, **Sarit Dhar**, Tamara Isaacs-Smith,* Auburn University*; Jacob Lawson, Charles Ebbing, Chase Kitzmiller, Joseph Merrit,* Air Force Research Laboratory, USA

The absence of shallow p-type dopants in $\beta\text{-}Ga_2O_3$ 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) $\beta\text{-}Ga_2O_3$ 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 $\beta\text{-}Ga_2O_3$, 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-38 Achievement of SiO₂/*β*-Ga₂O₃ (001) MOS Interface with Low in Terface State Density by Employing ALD with O₃ as an Oxidant and Low-temperature (600℃) Post-deposition Annealing*, **Atsushi Tamura**, Hayama Imaida, Koji Kita,* University of Tokyo, Japan

[Introduction] While a high-temperature (1000°C) O_2 annealing has been reported to efficiently reduce interface state density (D_{it}) in $SiO_2/\beta\text{-}Ga_2O_3$ MOS structures probably by removing oxygen deficiencies in the stack [1], it leads to serious drawbacks including the change in dopant profiles and a significant decrease in carrier density in $\beta\text{-}Ga_2O_3$ [2]. Therefore, it is essential to develop a low-temperature process to form $SiO_2/\beta\text{-}Ga_2O_3$ MOS interfaces. Taking into account of the necessity of oxygen deficiency removal as mentioned above,one of the keys is a selective oxidation of the $SiO_2/\beta\text{-}Ga_2O_3$ near-interface region. Therefore, atomic layer deposition (ALD) of SiO_2 is an attractive option because it enables us to tune the degree of oxidation in the initial stage of the film growth. In this study, we investigated the influence of oxidant supply conditions in ALD on the characteristics of $SiO_2/\beta\text{-}Ga_2O_3$ MOS interfaces with low-temperature (600°C) post-deposition annealing (PDA).

[Experimental] 11 nm-thick-SiO_2 films were deposited on n-type $\beta\text{-}Ga_2O_3$ (001) epi-wafers (N^D ~$10^{16}cm^{-3}$) at 300°C via ALD using TDMAS as a precursor. The initial 3 nm of SiO_2 was deposited using either O_2-remote-plasma-ALD or thermal-ALD employing O_3 as an oxidant, followed by an additional 8 nm of plasma-ALD. In the thermal-ALD, two kinds of O_3-doses per cycle (high or low-dose controlled by changing gas supply pulse duration) were employed. After PDA at 600°C in 0.1% O_2/N_2, Au gate electrodes were deposited.

[Results and Discussions] The sample fabricated via thermal-ALD with a high-dose of O_3 shows the minimum hysteresis width in the C-V curve among three samples. Regarding the energy distributions of D_{it}, its D_{it} is approximately one-third of that of the plasma-ALD sample, achieving approximately 1×10^{11} $eV^{-1}cm^{-2}$ at 0.2 eV below the conduction band edge. These results indicate that a sufficient O_3 supply to promote the oxidation of the near-interface region while avoiding plasma damage would be beneficial for reducing interface defect density with PDA at 600°C. Such a beneficial influence of employing O_3 as an ALD oxidant seems consistent with our previous results on $Al_2O_3/\beta\text{-}Ga_2O_3$ stacks [3]. This abstract is partly based on results obtained from a project, JPNP22007, commissioned by the New Energy and Industrial Technology Development Organization (NEDO).

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IWGO-TuP-39 Gallium Oxide-Based Photonic Memory Transistor for Nonvolatile Optoelectronic Applications*, Jiatong Dong,* King Abdullah University of Science and Technology, China*; Iman Roqan,* King Abdullah University of Science and Technology, Saudi Arabia

Gallium oxide (Ga_2O_3), as an ultra-wide bandgap semiconductor, has attracted significant attention for next-generation power electronics and solar-blind optoelectronic devices. In this work, we report a photonic memory transistor based on Ga_2O_3 integrated on a field-effect transistor platform, demonstrating its potential for nonvolatile optoelectronic memory applications.The device was fabricated by depositing Ga_2O_3 thin films onto the transistor usingPVD, followed by standard lithography and metallization processes. Upon ultraviolet (UV) illumination, the device exhibits photoresponse enabling memory behavior without continuous power supply. The charge trapping and detrapping processes in Ga_2O_3, likely associated with intrinsic defects such as oxygen vacancies, play a key role in the memory effect.Electrical characterization shows that the device demonstrates a memory window, high on/off ratio, and stable retention characteristics. The photo-programming and electrical erasing operations were systematically investigated, revealing tunable switching behavior and good repeatability. In addition, the dependence of the memory performance on illumination intensity and gate bias was analyzed to clarify the underlying physical mechanisms.These results highlight the feasibility of Ga_2O_3-based optoelectronic memory devices and provide insights into defect-engineered photonic memory functionalities. This work opens up new opportunities for integrating sensing and memory in a single wide-bandgap semiconductor platform.

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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 mΩ·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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