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Advanced Characterization Techniques
Room Jefferson 2-3 - Session AC-MoM
Characterization & Modeling I

Moderator: Kornelius Tetzner, Ferdinand-Braun-Institut, Leibniz-Institut für Höchstfrequenztechnik (FBH), Germany

9:30am **AC-MoM-5 Characterization of Deep Acceptors in β-Ga_2O_3 by Deep Level Optical Spectroscopy**, *H. Ghadi, J. McGlone, E. Cornuelle,* The Ohio State University*; A. Senckowski,* University of Massachusetts Lowell*; S. Sharma, U. Singisetti,* University of Buffalo*; M. Wong,* University of Massachusetts Lowell*; A. Arehart, **Steven A Ringel**,* The Ohio State University **INVITED**

Beta phase gallium oxide (β-Ga_2O_3) is a strong contender for next-generation high voltage and RF device applications. A key component of such devices is a semi-insulating, highly resistive buffer layer or substrate. To date, iron (Fe) has been the preferred acceptor impurity to achieve semi-insulating β-Ga_2O_3. Iron produces an energy level at E_C-0.8 eV, which has been substantiated by theoretical and experimental studies and enables highly resistive material. However, it has also been shown that residual Fe impurities can result in device switching instabilities since the Fermi level can modulate the occupancy of the Fe trap state during standard biasing conditions. While progress to mitigate the impact of residual Fe impurities has occurred, there is also interest in exploring acceptors with much deeper energy levels to avoid device instabilities. Magnesium (Mg) and nitrogen (N) have emerged as candidates based on their predicted energy levels of E_C-3.3 eV and E_C-2.8 eV, respectively (H. Peelaers, et al., APL Mater. 7, 022519, 2019). This presentation will compare each acceptor, with a primary focus on N, using deep level optical spectroscopy (DLOS) and thermally based deep level transient spectroscopy (DLTS). Here, N acceptors were introduced into HVPE-grown β-Ga_2O_3 by ion implantation. A uniform N-implantation profile was used targeting multiple doses in different samples, followed by an activation anneal. DLTS and DLOS measurements were applied before and after annealing. After implantation, multiple trap states appeared, most of which were removed by annealing, leaving a single, new state at E_C-2.9 eV, with Frank-Condon energy of 1.4 eV. The concentration of this state is monotonically tracked with nitrogen concentration from SIMS. This energy level closely matches predicted values for an acceptor-like defect due to nitrogen atoms occupying the oxygen III sites, determined by density functional theory (DFT) calculations (Y.K. Frodason, et al. J. Appl. Phys. 127, 075701, 2020), The much deeper energy compared with Fe could imply a significantly lower operational instability than the shallower Fe acceptor at E_C-0.8 eV. However, we found that the below midgap position of the $N_{O(III)}$ level, coupled with its small optical cross-section, complicates the trap concentration analysis by DLOS, which is important for understanding how to characterize very deep states in β-Ga_2O_3. Simultaneous hole emission to the valence band and electron emission to the conduction band was seen. The impact of this behavior on DLOS analysis is discussed, and a method to resolve this complication will be presented.

10:00am **AC-MoM-7 Determination of Cation Vacancy and Al Diffusion Constants in B-$(Al,Ga)_2O_3$ / Ga_2O_3 Superlattices**, *H. Yang, A. Levin, B. Eisner, A. Bhattacharyya, P. Ranga, S. Krishnamoorthy, **Michael Scarpulla**,* University of Utah

Cation vacancies have been implicated as the dominant compensating native defect in $(Al,Ga)_2O_3$, and will also mediate the diffusion of many impurities.The hidden influence of native defects on tracer diffusion e.g. of Si, Sn etc is critical to understand, especially in situations such as ion implantation where both tracer atoms and vacancies are introduced far above equilibrium concentrations and with spatial gradients.Additionally, cation vacancies and their accumulation at interfaces have been shown to determine the failure modes of high-power (Al,Ga)N devices.For these reasons, it is imperative to understand the diffusion of cation vacancies in $(Al,Ga)_2O_3$ and their mediation of substitutional diffusion of impurities and matrix atoms.This is clearly a difficult task compared, for example, to measuring tracer diffusion from surface sources.The formation energetics of cation vacancies, which is especially lowered by n-type doping in the $^{3-}$ and $^{2-}$ charge states, and their unusual structure have been computed and observed and much computational progress towards migration barriers has been made.

In this work we utilize $(Al,Ga)_2O_3$/Ga_2O_3 superlattices grown by OMVPE, annealing, SIMS profiling, and a novel finite differences simulation method to reveal and characterize the otherwise-invisible influence of cation vacancies. The diffusion of cations may have both interstitial and substitutional components; we present evidence showing that Al diffusion is probably dominated by the substitutional channel.The use of superlattices allows the differential measurement of Al diffusion at different depths, which in turn reveals gradients in the cation vacancy concentration and its evolution with annealing.For different samples, the initial concentration gradients of cation vacancies differ and diffusion occurs in a transient regime.Coupling these experiments with a model of coupled diffusion allows the extraction of the bare diffusion constant for the vacancies themselves (the hopping barrier alone, without formation enthalpy contributions), as well as determination of the Al diffusion constant including its dependence on vacancy concentration.Besides the fundamental interest in determining these parameters in single crystals (as opposed to prior polycrystalline work), these results will be critical for understanding crystal growth, ion implantation, and the time evolution of device structures subjected to extreme fields and temperatures.

10:15am **AC-MoM-8 Defect Characterization in Gallium Oxide and Related Materials Using Terahertz Electron Paramagnetic Resonance Ellipsometry: Fe in Ga_2O_3**, ***Mathias Schubert**,* University of Nebraska, Lincoln*; S. Richter,* Lund University, Sweden*; S. Knight, P. Kuehne,* Linkoping University, Sweden*; M. Stokey, R. Korlacki,* University of Nebraska-Lincoln*; V. Stanishev,* Linkoping University, Sweden*; Z. Galazka, K. Irmscher,* Leibniz-Institut fuer Kristallzuechtung, Germany*; S. Mu, C. Van de Walle,* University of California at Santa Barbara*; V. Ivády,* MPI Physics of Complex Systems, Germany*; O. Bulancea-Lindvall, I. Abrikosov,* Linkoping University, Sweden*; V. Darakchieva,* Lund University, Sweden

The control over electrical conductivity is critical key to enabling gallium oxide and related materials for high power electronic devices. Understanding the influence of dopants and defects onto the electrical and electronic properties is therefore of paramount importance [1]. Identifying defects and their local electronic properties remains a challenge. Here, we introduce frequency-domain Terahertz Electron Paramagnetic Resonance (EPR) ellipsometry as a new tool to study defects in gallium oxide and related materials at very high magnetic fields and very high frequencies. Traditional EPR methods exist in multiple variants and establish perhaps one of the most ubiquitous measurement techniques in science [2]. In our new concept, we determine the full polarization response of intricate defect spins as a continuous function of both field and frequency. For first investigations, we use our previously developed optical Hall effect setup [3]. We recently demonstrated this new approach analyzing the polarized spin response for the nitrogen defect in SiC [4]. Here, we investigate Fe-doped gallium oxide single crystals, and detect a large range of spin signatures which strongly vary with crystal orientation, frequency, and field. Iron is commonly used to obtain semi-insulating material where Fe2+ acts as compensating acceptor. The neutral defect Fe3+ is a high-spin system with s=5/2 and large zero-field splitting. Iron can incorporate at either Ga site but appears preferentially in octahedral configuration. Different claims exist about the nature of the spin Hamiltonian and approximate values for simplified orthorhombic models have been reported. We obtain the anisotropic g-factor as well as the zero-field Hamiltonian up to fourth order which allows to discuss the relevance of the monoclinic character of the local site symmetry. We compare our results with present knowledge from theory computation approaches. We further discuss the influence of phonons, strain, and local crystal symmetry, and we predict THz EPR ellipsometry as a new tool with potential for characterization of defects in heteroepitaxial systems.

[1] A. J. Greene et al., APL Materials 10, 029201 (2022).
[2] C. Poole, Electron Spin Resonance: A Comprehensive Treatise on Experimental Techniques (Wiley, New York, 1983).
[3] P. Kühne et al., IEEE Trans. Terahertz Sci. Technol. 8(3), 257 (2018).
[4] M. Schubert et al., Appl. Phys Lett. 120, 102101 (2022).

Bulk Growth
Room Jefferson 2-3 - Session BG-MoM
Bulk & Epitaxy I

Moderator: John Blevins, Air Force Research Laboratory

10:45am **BG-MoM-10 b-Ga_2O_3 Growth and Wafer Fabrication**, *A. Brady, G. Foundos, **Chase Scott**,* Northrop Grumman SYNOPTICS*; V. Gambin,* Northrop Grumman Corporation*; K. Stevens,* Northrop Grumman SYNOPTICS*; J. Blevins,* Air Force Research Laboratory, Afghanistan **INVITED**

SYNOPTICS began growing b-Ga_2O_3 under an AFRL contract FA8650-15C-1796 in 2015. Currently, 50mm diameter boules are consistently grown to

lengths up to 35mm from seeds oriented along the [010] direction. SYNOPTICS has grown boules as both unintentionally doped (UID) and doped with Mg and Fe using high purity (99.99+%) oxides to obtain semi- and highly insulating substrates. Doping levels for Mg were 0.10mol% and for Fe ranged from 0.0025mol% to 0.0100mol%.

Crystal growth is performed at the melting point of 1820°C via the Czochralski method using iridium crucibles in an induction-heated furnace using high purity Ga_2O_3 powder (99.999%). Ga_2O_3 is known to dissociate at high temperatures into sub-oxides including GaO and Ga_2O with O_2 evolution in oxygen-deficient atmospheres [1]. Growth in an iridium crucible, however, requires a low-oxygen environment to reduce oxidation of Ir to IrO_2 which leads to excessive crucible degradation and Ir-related defects in the crystal. SYNOPTICS growth chambers use free-flowing gas at ambient pressure to control the atmosphere. In order to suppress the dissociation of Ga_2O_3 and minimize excess oxidation of Ir, a mixed CO_2 and O_2 growth atmosphere is supplied to the melt surface. The crystals are rotated between 2 and 10 RPM and pulled at rates ranging between 0.5mm/hr and 2mm/hr during growth. Boules grown are largely free of twins and will occasionally have cleavage cracking on the (100) and (001) planes, the former being predominant.

The as-grown boules are oriented to within ~1° of the [010] growth axis and prepared for coring or shaping. 25mm diameter cores are drilled. 50mm diameter cores are obtained by turning down the entire boule on a lathe with a diamond tool. These cores are then encased in epoxy and sliced to ~700mm wafers using a multi-wire saw with a 150mm wire and B_4C loose abrasive slurry. The easily-cleaved (100) plane is used as the reference flat for wafers. The wafers are chemical mechanical polished to average surface roughness of <2Å via AFM scans of 20mm x 20mm. High resolution x-ray rocking curve measurements of the (020) show good crystal quality with FWHM of 63 arc-sec averaging parallel and perpendicular to the (100) reference flat respectively. Total thickness variation of less than 20 microns has been achieved on 50 mm epi-ready wafers.

References:

1. Z. Galazka et al., Cryst. Res. Technol. 45, No. 12, 1229 – 1236 (2010)

11:15am **BG-MoM-12 Increasing the Bandgap of β-Ga_2O_3 via Alloying with Al_2O_3 or Sc_2O_3 in Czochralski-grown Crystals***, **Benjamin Dutton,** J. Jesenovec, B. Downing, J. McCloy,* Washington State University

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Widening the bandgap of β-Ga_2O_3 is desirable for improving the critical breakdown field and enabling transmission further into the ultraviolet. In this work, alloyed β-Ga_2O_3 bulk single crystals were grown by the Czochralski and vertical gradient freeze methods with batched alloy compositions of β-$(Sc_{0.1}Ga_{0.9})_2O_3$ (10 mol.% Sc_2O_3, SGO) and β-$(Al_{0.1}Ga_{0.9})_2O_3$ (10 mol.% Al_2O_3, AGO). Dopant incorporation and site occupancy were analyzed by X-ray fluorescence and nuclear magnetic resonance, respectively. Al incorporated more readily into the Czochralski pulled crystal with approximately 11.7 mol.% Al_2O_3 present, while only 6.2 mol.% Sc_2O_3 incorporated into the Czochralski pulled SGO crystal.Lattice changes were characterized by powder X-ray diffraction, X-ray rocking curve, and Raman spectroscopy, with AGO exhibiting higher crystal quality than SGO. Optical transmission measurements (200 nm – 20 µm) indicated a shift to a larger bandgap in both AGO and SGO compared to undoped β-Ga_2O_3. AGO samples were highly insulating, with resistivities on the order of 10^{11} Ω·cm, while SGO samples exhibited resistivities in the range of 10^1 - 10^2 Ω·cm. SGO exhibited luminescence characteristic of rare earth element impurities, originating from the Sc_2O_3 precursor powder. AGO in general appears to be a better candidate for producing epi-ready substrates compared to SGO, due to better lattice match and improved incorporation into the growing crystal without precipitation of secondary phases.

11:30am **BG-MoM-13 Chemi-Mechanical Polishing and Subsurface Damage Characterization of 2-inch (010) Semi-Insulating β-Ga_2O_3 Substrates***, **David Snyder,*** Penn State Applied Research Laboratory

Results will be presented for the development of a high removal rate 2-step chemi-mechanical polishing (CMP) process for epi-ready 2-inch semi-insulating (010) β-Ga_2O_3 substrates grown by the Czochralski process at SYNOPTICS.First, the depth of subsurface damage was characterized to determine how much material needed to be removed from the surface. Using a combination of x-ray rocking curves (XRRC's) and cross-sectional SEM imaging the maximum depth of damage was shown to be on the order of 75 µm after multi-wire sawing with 150 µm wire and B4C loose abrasive slurry.This was significantly deeper than predicted from abrasive size correlations and surface roughness measurements of the as-sawn wafers.

To minimize processing time, we developed a two-step polishing process with the target removal of 75 µm using an intermediate process and 25 µm using a final CMP step. For the initial step, several options for polishing slurries, including colloidal alumina and diamond, were evaluated. To further understand and quantify subsurface damage we used in-line x-ray diffraction (XRD). Unmounted wafers were characterized, and we also developed custom polishing plates that could be mounted within a high-resolution XRD system so that rocking curves could be collected at intermediate points in the process without removing wafers from the polishing plate.These scans were collected as a function of removal amount and were found to be surprisingly sensitive to subsurface damage.Excellent results were achieved with 1-3 µm diamond with very high removal rates on the order of 25 µm/hr resulting in a process time of only 3 hrs for the initial 75 µm removal

Subsequently, we studied alternative final CMP steps and identified two options as promising final steps.We studied pH modified colloidal silica over the pH range of~3 to 9.At a pH of 4, we were able to get extremely low surface roughness values (<2 Å) and excellent XRRC FWHM values (40 arcsec) while increasing removal rate by ~2.5X to nearly 1.0 µm/hr.Similar results were obtained using pH modified nano-diamond providing a potential route to a non-silica based polishing process.

11:45am **BG-MoM-14 Ge-Delta Doped *β*-Ga_2O_3 Grown Via Plasma Assisted Molecular Beam Epitaxy***, **Thaddeus Asel,*** Air Force Research Laboratory, Materials and Manufacturing Directorate, USA*; E. Steinbrunner,* Wright State University, Department of Electrical Engineering*; J. Hendrick,* Air Force Institute of Technology, Department of Engineering Physics*; A. Neal, S. Mou,* Air Force Research Laboratory, Materials and Manufacturing Directorate, USA

We utilized secondary ion mass spectroscopy (SIMS) and capacitance voltage measurements to develop the capability to delta dope *β*-Ga_2O_3 thin films with Germanium grown via plasma assisted molecular beam epitaxy (PAMBE). Doping PAMBE grown *β*-Ga_2O_3 has proven to be a challenge in the community. Early Si delta doping studies showed promise with a Si background of 1×10^{17} cm^{-2} with good sheet carrier concentrations of 1.2×10^{13} cm^{-2}.[1] However, the quartz plasma bulb has been demonstrated to be a source of unintentional Si doping. Additionally, a background can be observed from the Si cell itself when it is left hot in the chamber with the shutter closed during growth.[2] This effect appears to be based on chamber geometry as it is not consistent from system to system, but does prevent Si from being consistently used for delta doping studies. Ge is another n-type dopant that could allow for delta doped structures to be grown via PAMBE. There are difficulties tuning Ge doping in *β*-Ga_2O_3, such as the sensitivity of substrate temperature where the Ge doping can vary over two orders of magnitude over a 100 °C range. Site competition occurs as well, as the Ga beam flux is increased during growth, the Ge concentration will drop as well. Uniform doping with Ge seems unlikely as the Ge incorporation decreases as a function of time, indicating that the ge source material is oxidizing during the growth. However, the background doping caused by Ge is in the range of 1-7 × 10^{15} cm^{-3} as seen in SIMS as opposed to 1×10^{18} cm^{-3} for Si in our chamber. Doping with Ge up to 5×10^{19} cm^{-3} has been achieved as well. This suggests Ge is a good candidate for delta doping applications. Using a Ge cell temperature of 700 °C, a substrate temperature of 550 °C, a delta doped structure that was capped with 50 nm of unintentionally doped *β*-Ga_2O_3 was grown and then measured by CV. The CV profile revealed a sharp peak at 58 nm into the sample with an integrated sheet concentration of 1×10^{13} cm^{-2} and a peak width of 12 nm at 10% of the maximum volume concentration. In summary, this demonstrates that Ge is a good dopant choice for delta doping in PAMBE, providing a lower background density than that of Si doping.

[1] Z. Xia, C. Joishi, S. Krishnamoorthy, S. Bajaj, Y. Zhang, M. Brenner, S. Lodha, and S. Rajan, IEEE Electron Device Letters **39**, (4) 568-571 (2018).

[2] T.J. Asel, E. Stein Brunner, J. Hendricks, A.T. Neal, and S. Mou,J. Vac. Sci. Technol. A **38**, 043403 (2020).

12:00pm **BG-MoM-15 High Purity n-type β-Ga_2O_3 Films with 10^{13} cm^{-3} Residual Accepter Concentration by MOCVD***, **Andrei Osinsky**, F. Alema,* Agnitron Technology

MOCVD growth of epitaxial Ga_2O_3 films using TMGa precursor has not been widely investigated due to its challenges with carbon incorporation and difficulty in realizing device quality films. However, given its high vapor pressure and shorter reaction kinetics, it offers a fast growth rate,which is vital for Ga_2O_3 based high voltage power devices that require tens of microns of layer thickness. With optimal process conditions and a suitable MOCVD reactor, the TMGa precursor has the potential to produce films with comparable or even better material quality to those grown using the more popular TEGa precursor. In this work, we will present the growth of high purity homoepitaxial β-Ga_2O_3 thin films by using a TMGa precursor with LT electron mobility exceeding 23,000 cm^2/Vs and acceptor concentration of $2x10^{13}$ cm^{-3}[1]. A wide range of controllable doping of TMGa grown Ga_2O_3 films with Ge and Si dopants will be discussed. Smooth films with RT electron mobility of >130 cm^2/Vs for n ~$3x10^{17}$ 1/cm^3 have been demonstrated. Temperature-dependent Hall measurement will be used to identify the nature of impurities in the TMGa grown films lightly doped with Ge and Si and the results will be compared with TEGa grown films doped in similar conditions. The obtained results confirm the suitability of TMGa precursor for the growth of high purity β-Ga_2O_3 films at a fast growth rate, meeting the demands for commercializing Ga_2O_3 based high voltage power devices by MOCVD. In this presentation, we will also report on the intentional doping of Ga_2O_3 films with nitrogen and carbon to grow semi-insulating films.

[1] G. Seryogin, et al. Appl. Phys. Lett. **117** 262101 (2020).

Keynote Address
Room Jefferson 2-3 - Session KEY1

Keynote Address
Moderator: Dr. Kelson Chabak, Air Force Research Laboratory

8:45am **KEY1-2 Keynote Lecture: Ga_2O_3 Device Technologies: Power Switching and High-Frequency Applications, and Beyond***, **Masataka Higashiwaki,*** Department of Physics and Electronics, Osaka Metropolitan University, Japan*; T. Kamimura, S. Kumar, Z. Wang,* National Institute of Information and Communications Technology, Japan*; T. Kitada, J. Liang, N. Shigekawa,* Department of Physics and Electronics, Osaka Metropolitan University, Japan*; H. Murakami, Y. Kumagai,* Department of Applied Chemistry, Tokyo University of Agriculture and Technology, Japan **INVITED**

Developments of Ga_2O_3 field-effect transistors (FETs) and diodes are being actively conducted all over the world. From the world-first demonstration of single-crystal Ga_2O_3 FETs in 2011 [1], we have been developing both vertical and lateral Ga_2O_3 devices. In this talk, our latest selected challenges on vertical Ga_2O_3 Schottky barrier diodes (SBDs), vertical Si/Ga_2O_3 heterostructures, and lateral short-gate Ga_2O_3 FETs will be discussed.

Ga_2O_3 SBDs with a trench staircase field plate were fabricated [2]. We found that the staircase field plate on the deep trench filled with SiO_2 can effectively alleviate electric field concentration in both the Ga_2O_3 drift layer and the SiO_2. The Ga_2O_3 SBDs successfully demonstrated superior device characteristics including an on-resistance of 7.6 mΩcm^2 and an off-state breakdown voltage of 1.66 kV.

Next, our pioneering work on vertical n-Si/n-Ga_2O_3 heterostructures fabricated using surface-activated bonding will be presented [3]. Analyses of temperature-dependent current density–voltage characteristics of the heterostructures revealed that an energy barrier was formed at the Si/Ga_2O_3 heterojunction interface due to negatively charged interface states. The conduction band offset at the bonding interface was estimated to be 0.18 eV.

We have also been developing lateral Ga_2O_3 FETs with a highly scaled gate for high-frequency and logic applications in harsh environments. Submicron-gate Ga_2O_3 FETs with a thin channel layer formed by Si-ion implantation doping achieved promising device performance typified by a maximum oscillation frequency of 27 GHz at a gate length of 200 nm [4].

These works were supported in part by the Ministry of Internal Affairs and Communications (MIC) research and development (JPMI00316) and JSPS KAKENHI Grant Number 19H02182, Japan.

[1] M. Higashiwaki, K. Sasaki, A. Kuramata, T. Masui, and S. Yamakoshi, Appl. Phys. Lett. **100**, 013504 (2012).

[2] S. Kumar, H. Murakami, Y. Kumagai, and M. Higashiwaki, Appl. Phys. Express, *in press*.

[3] Z. Wang, D. Takatsuki, J. Liang, T. Kitada, N. Shigekawa, and M. Higashiwaki,J. Appl. Phys. **131**, 074501 (2022).

[4] T. Kamimura, Y. Nakata, and M. Higashiwaki, Appl. Phys. Lett. **117**, 253501 (2020).

Material and Device Processing and Fabrication Techniques
Room Jefferson 2-3 - Session MD-MoA
Process & Devices I

Moderator: Man-Hoi Wong, University of Massachusetts Lowell

1:45pm **MD-MoA-1 High Aspect Ratio Ga_2O_3-based Homo and H0eterostructures by Plasma-free Metal-assisted Chemical Etching**, ***Xiuling Li,*** University of Texas at Austin*; H. Huang, C. Chan, J. Michaels,* University of Illinois, Urbana-Champaign **INVITED**

β-Ga_2O_3, with an ultra-wide bandgap (UWB) of ~ 4.8 eV and bulk substrate availability, has drawn enormous interests in the power electronics and solar-blind optoelectronics community. Fabricating high-aspect-ratio β-Ga_2O_3 3D nanostructures without surface damage is essential for next-generation high power and high speed devices. However, dry etch typically damages the surface due to the high-energy ions, while most wet etching techniques can only produce very limited aspect ratios.

Metal-assisted chemical etch (MacEtch) is an unorthodox anisotropic chemical etching method, that defies the isotropic nature of chemical etch through metal catalysis effect and enables site-controlled semiconductor nanostructure fabrication with unpresented aspect ratio (e.g. > 200:1 for Si) and versatility. Since it was first developed for open-circuit porous silicon formation, catalyst-site-specific MacEtch has enabled the formation of nanostructures of a broad range of semiconductors, including silicon, germanium, III-As, III-P, III-N, SiC, and oxides, as well as some of their heterostructures. The versatility of MacEtch is also evident in the unique characteristics of different types of MacEtch. Inverse-MacEtch (i-MacEtch) allows the formation of atomically smooth sidewalls; magnetic-field guided MacEtch (h-MacEtch) enables 3D control of the etching trajectory; Self-Anchored Catalyst MacEtch (SAC-MacEtch) promotes the sidewall verticality for large via by using porous catalyst; UV-assisted MacEtch (UV-MacEtch) makes plasma-free wide-bandgap semiconductor etch possible; and the ultimate vapor phase MacEtch (VP-MacEtch), while maintaining the damage-free nature, truly takes the technology towards scalability and manufacturability, including the successful demonstration of CMOS compatible titanium nitride (TiN) catalyzed etch. The simplicity, versatility, manufacturability, and realistic potential of MacEtch make it well-positioned to enhance or replace dry etch methods for future generation of 3D transistors, through-silicon-vias, trench memory, thermoelectric, detectors, and photovoltaic devices.

In this talk, high aspect ratio β-Ga_2O_3 nanofins and AlGaO/GOX nanostructures fabricated by inverse metal-assisted chemical etching (MacEtch), under UV light irradiation, will be presented. The etched surface and interface properties, including Schottky barrier height and interface trap density, will be characterized for device applications.

2:15pm **MD-MoA-3 Blocking Behavior of N and Fe Ion Implanted β-Ga_2O_3**, ***Bennett Cromer,*** Cornell University*; W. Li,* University of California at Berkeley*; K. Smith,* Cornell University*; K. Gann,* Cornell University, Iceland*; K. Nomoto,* Cornell University*; N. Hendriks,* University of California at Santa Barbara*; A. Green, K. Chabak,* Air Force Research Laboratory*; M. Thompson, D. Jena, G. Xing,* Cornell University

β-Ga_2O_3 is an actively studied material for high power devices, largely due to its high breakdown electric field of 8 MV/cm and commercially available substrates. Due to the lack of effective p-type conduction in Ga_2O_3, state of the art devices utilize implantation of deep acceptors and heterojunctions for edge termination and device isolation. Implantation of deep acceptors such nitrogen and magnesium have yielded semi-insulating behavior under quasi-static conditions[1]. Nitrogen, specifically, exhibited long-lasting charge trapping in partially activated devices which suggests some time-dependent blocking ability. [2]. This begs the question: Does the semi-insulating behavior of N-implantation change significantly with frequency? Further, despite being ubiquitous in insulating Ga_2O_3 substrates, Iron has yet to be implanted and studied for select-area isolation. Key information such as activation temperature and frequency response is not known. In this work, we utilize N and Fe ion implantation to fabricate metal-"insulator"-semiconductor, field-plated, and Schottky barrier diode structures to evaluate the resistive behavior of N- and Fe-implanted Ga_2O_3.

Ni-β-Ga_2O_3 diodes were fabricated on (001) 10 µm HVPE epitaxial substrates. Prior to implantation, photolithography was used to create areas under the anode that were blanket implanted (MIS), partially implanted (field-plated), and un-implanted (SBD). The N- and Fe-implanted samples underwent recovery annealing prior to cathode Ti/Au and anode Ni/Au contacts deposited by e-beam evaporation, aligned to the implanted regions.

We remark that N-implanted MIS structures exhibit reduced forward current by a factor of 10^3 and no significant enhancement of the breakdown voltage compared to comparative un-implanted SBDs. Pulsed I-V reveals that below pulse-widths of 5 us, corresponding to a frequency of 200 kHz, N-implanted regions behave similarly to bulk Ga_2O_3 and does not act as blocking. Fe-implanted MIS structures, by comparison, exhibit reduced forward current by 10^8, enhanced breakdown voltage, and minimal dependence on frequency.

Acknowledgements: We acknowledge support from the AFOSR Center of Excellence Program FA9550-18-1-0529. This work was performed in part at the Cornell Nanoscale Facility, a NNCI member supported by NSF grant NNCI-2025233.

[1] M. H. Wong *et al.*, "Acceptor doping of β-Ga2O3 by Mg and N ion implantations," *Appl. Phys. Lett.*, Sep. 2018.

[2] M. Fregolent *et al.*, "Impact of thermal annealing on deep levels in nitrogen-implanted β-Ga2O3 Schottky barrier diodes," *J. Appl. Phys.* Dec. 2021.

2:30pm **MD-MoA-4 Evolution and Recovery of Ion Implantation-Induced Damage Zone in β-Ga2O3**, ***Elaf Anber,*** *D. Foley, J. Nathaniel,* Johns Hopkins University*; A. Lang ,* American Society for Engineering Education*; J. Hart ,* Johns Hopkins University*; M. Tadjer, K. Hobart,* US Naval Research Laboratory*; S. Pearton,* University of Florida, Gainesville*; M. Taheri,* Johns Hopkins University

β-Ga2O3 has drawn substantial attention due to its large band gap, high electric breakdown field, and high thermal stability [1-4].These properties make β-Ga2O3 a promising material for application in harsh environments including high temperature and high radiation dose applications [3].However, the structural complexity of β-Ga2O3, including the two different crystallographic positions of Ga, and numerous crystallographic polymorphs, lead to a large number of complex defects which can form due to radiation exposure [4]. While radiation damage of β-Ga2O3 has been studied recently, to date, no study has focused on the structural defects arising from ion implantation. Therefore, in this study we examine β-Ga2O3 in three conditions:as-received,as implanted with Ge with a concentration of ~1020 cm-3 , and implanted-annealed at 1150°C for 60 seconds [5]. We analyze these samples using analytical electron microscopy via scanning/transmission electron microscopy (S/TEM), and electron energy loss spectroscopy(EELS). Additionally, precession electron diffraction was utilized to measure strain induced from complex defects formed upon radiation. Electron microscopy imaging revealed an isolated band of structural damage after Ge implantation, which extended ∼130 nm from the sample surface and corresponds to the projected range of the ions. Electron diffraction demonstrates that the entirety of the damage band is the κ phase, indicating an implantation-induced phase transition from β to κ-Ga_2O_3. Post-implantation annealing at 1150 °C for 60 s under an O_2 atmosphere a return from κ to β; however, an ∼17 nm damage zone remained at the sample surface. These data indicate differences in the electronic/chemical structure beyond the implantation zone (∼130 nm) due to the diffusion of Ge into the bulk material, which, in turn, causes a change in material properties[5]. Outstanding questions remain regarding the ability to have a full reversal to the original crystal structure, and the ability to do so represents a major milestone for use of these materials in next generation electronics.

To answer these outstanding questions, in-situ transmission electron microscopy annealing will be performed to study the role of Ge. Implanted Ga2O3 will be analyzed using high resolution electron microscopy imaging for structural analysis, coupled with electron energy loss spectroscopy for chemical analysis. Electronic structure and atomic bonding of Ga-O will be monitored throughout various stages of the annealing treatments.

2:45pm **MD-MoA-5 Heterogeneous Integration of Single-Crystal β-Ga_2O_3 and N-Polar GaN Substrates With ZnO Interlayer Deposited by Atomic Layer Deposition**, ***Zhe (Ashley) Jian,*** University of Michigan, Ann Arbor*; C. Clymore,* University of California, Santa Barbara*; D. Agapiou,* University of Michigan, Ann Arbor*; U. Mishra,* University of California, Santa Barbara*; E. Ahmadi,* University of Michigan, Ann Arbor

Recently, β-Ga_2O_3 has attracted great attention as a promising candidate for high power switching applications. However, two main challenges of β-Ga_2O_3 are its relatively low electron mobility (180 $cm^2V^{-1}s^{-1}$) and low thermal conductivity (10-30 W/m·K) [1], [2]. Additionally, p-type doping does not seem feasible currently for this material system. On the other

hand, GaN, a well-known wide bandgap semiconductor, has a high electron mobility (2050 $cm^2V^{-1}s^{-1}$), high 2D charge (2DEG) density, moderate thermal conductivity (253 W/m·K), and the availability of p-type doping [3]. Therefore, the integration of β-Ga_2O_3 with GaN can potentially enable the fabrication of novel GaN/Ga_2O_3 high-frequency and high-power devices combining the merits of both GaN and Ga_2O_3 in addition to novel optoelectronic devices.

This work integrated single-crystal (0001) N-polar GaN and (-201) UID β-Ga_2O_3 substrates via wafer bonding using ZnO interlayer deposited by atomic layer deposition (ALD). Both 5×5 mm^2 GaN and 10×10 mm^2 Ga_2O_3 substrates were soaked in buffered hydrofluoric acid (BHF) for 30 seconds prior to the deposition of 10 nm-thick ZnO via thermal-ALD at 200 °C. Next, the Ga_2O_3 and GaN samples were placed into contact with each other. The bonding was conducted at 400 °C under the pressure of 4 MPa. The surfaces were 100% fully bonded. After bonding, both the front and back sides of the sample were evaporated by Ti/Au. To investigate the impact of post-annealing temperature on the bonding interfaces, the N-polar GaN/ZnO/Ga_2O_3 test structure was annealed in N_2 for 30 minutes at temperatures of 600 °C and 900 °C.

Temperature dependent I-V measurements were performed on the GaN/ZnO/Ga_2O_3 test structure at temperatures from 300 K to 650 K with step increment of 25 K. As-bonded sample without annealing demonstrated Schottky behavior. The Schottky barrier of around 0.56 eV was extracted from a linear fit to the Richardson plot. After annealing at 600 °C, the I-V curves showed almost linear behaviors, indicating that the test structure could be modeled by a series resistor. The maximum current density of 0.02 A/cm^2 at V_{bias} = 6 V and the resistance of 1714 Ω were measured at room temperature. Additionally, increasing the annealing temperature to 900 °C caused a substantial change in the I-V-T characteristics.

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[2] Z. Feng et al., Appl. Phys. Lett., vol. 114, no. 25, p. 250601, Jun. 2019.

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3:00pm **MD-MoA-6 Structural Transformation of β-Ga_2O_3 through Si-implantation***, **Snorre Braathen Kjeldby**, A. Azarov, P. Nguyen,* Centre for Materials Science and Nanotechnology, University of Oslo, Norway*; V. Venkatachalapathy,* Centre for Materials Science and Nanotechnology, University of Oslo and Department of Materials Science, National Research Nuclear University, "MEPhl", Norway*; R. Mikšová,* Nuclear Physics Institute of the Czech Academy of Sciences, Czechia*; A. Macková,* Nuclear Physics Institute of the Czech Academy of Sciences and Department of Physics, Faculty of Science, J.E. Purkyně University, Czechia*; J. García-Fernández, A. Kuznetsov, Ø. Prytz, L. Vines,* Centre for Materials Science and Nanotechnology, University of Oslo, Norway

Implantation doping is important in device fabrication, but the understanding of the process in β-Ga_2O_3 remains incomplete. In particular, recent works have shown that polymorph transformations can occur in ion-implanted β-Ga_2O_3[1,2]. If such a transformation also occurs for Si- and Sn-implantation, it could potentially impact donor implantation and detrimentally affect device fabrication. On the other hand, the transformation may open new fabrication routes, e.g. templated growth of other Ga_2O_3 polymorphs. In the present work, we undertook a systematic investigation of Si-implantation in Ga_2O_3, focusing on the effects of implantation fluence and post-implantation annealing temperature on the crystal structure of the sample[3].

EFG-grown bulk (-201)-β-Ga_2O_3 samples were implanted with 300 keV $^{28}Si^+$-ions at room temperature to fluences in the 1 × 10^{14}-2 × 10^{16} Si/cm^2 range. We then exposed the samples to annealing in air between 300 and 1300 °C. Rutherford backscattering spectrometry in channeling mode (RBS/c) and X-ray diffraction (XRD) were used for characterization after every step. Samples implanted to fluence 2 × 10^{16} Si/cm^2 (as-implanted and annealed at 1100 °C) were characterized with (scanning) transmission electron microscopy [(S)TEM].

For fluences of 1 × 10^{15} Si/cm^2 and above, XRD revealed emergence of additional diffraction peaks in the as-implanted samples (Figure 1). We attributed these diffraction peaks to structural transformation in the implanted layer. After annealing at 700 °C, these features disappeared, and the XRD results were consistent with a return to the β-phase, further supported by the RBS/c results.

In (S)TEM, selected area electron diffraction patterns from the implanted layer in the as-implanted sample had hexagonal symmetry, consistent with previous reports for implantation of other species, where it was interpreted as a β-to-κ polymorph transformation[1,2]. Our data also show a crystalline-to-crystalline phase transformation, although the data were not fully consistent with identification of the transformed structure as κ-Ga_2O_3[3]. For the annealed sample, (S)TEM revealed that the implanted layer consisted of defective β-Ga_2O_3. Finally, electron energy loss spectroscopy demonstrated accumulation of Si into SiO_2 nanoparticles in the implanted layer after annealing, which could reduce the doping efficiency for high implantation fluences.

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3:15pm **MD-MoA-7 Electrical Characteristics of *in Situ* Mg-Doped Ga_2O_3 Current-Blocking Layer for Vertical Devices***, **Sudipto Saha**,* University at Buffalo-SUNY*; L. Meng, A. Bhuiyan, Z. Feng, H. Zhao,* Ohio State University*; U. Singisetti,* University at Buffalo-SUNY

Monoclinic beta-gallium oxide (Ga_2O_3) has recently attracted tremendous interest in power electronics and RF switching applications due to its ultrawide bandgap. Vertical devices are generally preferred over lateral geometries for power electronics applications due to the absence of surface effects. Vertical Ga_2O_3 transistors with a current blocking layer (CBL) could potentially achieve kilo-volt ratings. Due to the deep acceptor nature of Mg in Ga_2O_3, Mg-doped Ga_2O_3 layers can potentially form CBLs, critical for high voltage power devices.

In this work, we demonstrate *in-situ* Mg doping in MOCVD-grown films. Two vertical n-CBL-n structures, n-Ga_2O_3/Ga_2O_3:Mg/n-Ga_2O_3, and n-Ga_2O_3/ Ga_2O_3:Mg/UID-Ga_2O_3/n-Ga_2O_3, labeled as S1-FD and S2-PD, were grown to study and assess the blocking capability of Mg-doped Ga_2O_3. The thickness of the Mg-doped CBL for S1-FD and S2-PD are 500 nm and 250 nm, respectively. The Mg target doping density is 1x10^{19} cm^{-3}. Two-terminal diode structures were fabricated, and systematic electrical characterizations were performed to compare the electrical properties of the two structures. While sweeping voltage from -10 V to 10 V, S1-FD showed better current blocking capability compared to S2-PD, indicating the dependence of Mg-doped layer thickness on the current blocking capability. With the increase of temperature up to 300 ^oC, the forward blocking voltage (V_{fb}) decreased from 10 V to 5.53 V for S1-FD, whereas V_{fb} remains pretty unchanged (~6 V) for S2-PD with the rise of temperature. S1-FD structure showed a higher reverse leakage current (0.14 nA/µm^2 at -10 V) compared to S2-PD (1.5 x 10^{-4} nA/µm^2 at -10 V). S2-PD gave a destructive reverse breakdown voltage of 35 V with ~ 1.6 MV/cm average field strength.

From the analysis of the device *J-V*s of the two structures, it's hypothesized that with the increased Mg-doped CBL thickness, the forward blocking capability increases but the reverse leakage current increases as well. Further investigation of the interplay between leakage and blocking voltage due to Mg dopants is needed. TCAD simulation of the current-voltage characteristics shows that the effective acceptor doping is 1x10^{17} cm^{-3}. Optimization of the growth conditions can increase the accepter activation efficiency. The development of an *in situ* acceptor doping technology for Ga_2O_3 creates unique opportunities for designing and engineering a variety of high-voltage Ga_2O_3 devices.

Theory, Modeling and Simulation
Room Jefferson 2-3 - Session TM-MoA

Characterization & Modelling II

Moderator: Mike Thompson, Cornell University

3:45pm **TM-MoA-9 Transport, Doping, and Defects in β-Ga_2O_3***, **Adam Neal**,* Air Force Research Laboratory, Materials and Manufacturing Directorate, USA **INVITED**

The first reports of Ga_2O_3 MESFETs and MOSFETs by the group of Higashiwaki demonstrated the potential of β-Ga_2O_3 for high breakdown voltage, low on-resistance power electronics due to its ultra-wide bandgap and large breakdown electric field. Realizing that potential requires development of high-quality β-Ga_2O_3 material, best guided by an understanding of the electronic transport properties which directly correlate to device performance. In this talk, through a combination of temperature dependent Hall effect and admittance spectroscopy

measurements, I will begin by presenting our work characterizing electrically active defects which may ultimately limit the maximally achievable breakdown voltages in Ga_2O_3 devices. Following that, I will present analysis of transport in plasma-MBE grown β-Ga_2O_3 produced at Air Force Research Laboratory, towards understanding the contributions of various scattering mechanisms limiting the electron mobility in our films. Informed by transport studies such as these, material growers and device engineers can continue to push β-Ga_2O_3 to the limits of its performance.

4:15pm **TM-MoA-11 Structural Changes to Beta Gallium Oxide from Ion Irradiation Damage: Model and Relation to in-Situ Experiments***,* ***Alexander Petkov****, D. Cherns, D. Liu,* University of Bristol, UK*; W. Chen, M. Li,* Argonne National Laboratory, USA*; J. Blevins,* Air Force Research Laboratory, USA*; V. Gambin,* Northrop Grumman*; M. Kuball,* University of Bristol, UK

A good radiation hardness of Ga_2O_3 has been suggested, though its susceptibility to radiation damage is higher than in GaN. To better assess gallium oxide device reliability for nuclear and space applications, more understanding of the structural changes in the material as a result of irradiation is needed. We propose a model for the structural deformation of beta gallium oxide under ion irradiation. Assuming displacements confined primarily to the Ga-atom sublattice, we explain the main features of TEM diffraction patterns from in-situ irradiated gallium oxide using 400 eV Ar ions of fluence 4×10^{15} cm^{-1} (equivalent to 2 displacements per atom) (Fig. 1). We propose that displacements of gallium atoms are confined between close-packed O-atom layers (which in beta gallium oxide exist parallel to the (101), (-201), (-3-10), (-310) planes) with a preference for octahedral interstitial positions and recombination. We thus demonstrate the anisotropic evolution of the octahedral-to-tetrahedral Ga-site ratio in the irradiated gallium oxide as a function of displacements per atom, finding it to increase the most along the [-3-10] direction and the least along the [-201] (Fig. 2). The similarity of the structure post irradiation with that of kappa and alpha gallium oxide is examined. We conclude that while the structure post irradiation shares some features similar to kappa gallium oxide (specifically the octahedral-to-tetrahedral site ratio), ion irradiation does not cause a phase transition of beta gallium oxide into kappa as previously thought (Fig. 3).

The authors gratefully acknowledge the NSUF funding (#1393) for beamtime at Argonne IVEM-Tandem User Facility. The authors also thank Mr Peter Baldo (ANL, USA) for dedication on the operation of the ion accelerator during the experiment.

4:30pm **TM-MoA-12 Band Structure Across κ-$(In_xGa_{1-x})_2O_3$/κ-$(Al_yGa_{1-y})_2O_3$ Thin Film Interfaces***,* ***Ingvild Julie Thue Jensen****, A. Thøgersen, E. Fertitta, B. Belle,* SINTEF Materials Physics, Norway*; A. Langørgen, S. Cooil, Y. Hommedal, Ø. Prytz, J. Wells, L. Vines,* University of Oslo, Norway*; H. von Wenckstern,* University of Leipzig, Germany

Ga_2O_3 is a candidate for development of power electronics components that are faster, smaller and more energy efficient than Si-based technology, permitting devices capable of operating at higher voltages, frequencies and temperatures.[1] The κ-phase of Ga_2O_3 (sometimes labeled ε-phase) is a meta-stable orthorhombic phase where large spontaneous polarization has been predicted by density functional theory.[2] By partial substitution of Ga by In or Al, the original bandgap (~4.9 eV) can be decreased or increased, in principle within the range spanned by the bandgaps of In_2O_3 (2.9 eV) and Al_2O_3 (8.8 eV).This provides a wide parameter space for device development through tailoring of properties such as bandgaps and band offsets. It is believed that interface-localized two-dimensional electron gas (2DEG) may be achieved within this materials system, which opens for potential applications in *so-called* high-electron-mobility transistors (HEMTs).

In the present work the band structure of thin film κ-$(In_xGa_{1-x})_2O_3$/κ-$(Al_yGa_{1-y})_2O_3$ heterostructures are investigated experimentally to evaluate if formation of 2DEG can be within reach. Samples with a selection of *x* and *y* compositions were fabricated by Pulsed Laser Deposition (PLD) on sapphire substrates. Both synchrotron and in-house X-ray Photoelectron Spectroscopy (XPS) were used to investigate the position of the valence band edges relative to the Fermi level in the heterostructure layers and corresponding reference samples. Extraction of valence band maxima from XPS was aided by Density functional theory (DFT) calculations. Local bandgap information was provided by Scanning Transmission Electron Microscope Electron Energy Loss Spectroscopy (STEM EELS), which can determine wide bandgaps with a spatial resolution < 10 nm. Valence band offsets across the heterojunctions were obtained by XPS and combined with bandgap information to find the corresponding conduction band offsets and provide a comprehensive overview of band discontinuities across κ-$(In_xGa_{1-x})_2O_3$/κ-$(Al_yGa_{1-y})_2O_3$ interfaces.

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4:45pm **TM-MoA-13 Aluminum Incorporation Striations in (-201) β-$(Al_xGa_{1-x})_2O_3$ Films Grown on C-Plane and Miscut Sapphire Substrates***,* ***Kenny Huynh****, Y. Wang, M. Liao,* University of California Los Angeles*; P. Ranga,* University of Utah*; S. Krishnamoorthy,* University of California at Santa Barbara*; M. Goorsky,* University of California, Los Angeles

High aluminum content striations were observed in (-201) $(Al_xGa_{1-x})_2O_3$ thin films (~500 nm) grown on (0001) and 6° miscut (0001) sapphire substrates. A modulated Al composition structure was observed whose orientation depended on the substrate miscut. High resolution x-ray diffraction (XRD) and transmission electron microscopy (TEM) were used to investigate the structural and chemical properties of the $(Al_xGa_{1-x})_2O_3$ films (with $0<x<0.3$) and the in-plane relationship with the underlying sapphire substrate. (-201) $(Al_xGa_{1-x})_2O_3$ films were grown by metalorganic vapor phase epitaxy and the Al composition was controlled by tuning the ratio of trimethylaluminum to triethylgallium flow. The growth was carried out at a substrate temperature of 810 °C and a reduced growth pressure of 15 Torr to minimize Al precursor prereactions.

Scanning transmission electron microscopy measurements (sensitive to Z-contrast) reveal alternating layers of high and low contrasting features throughout the $(Al_xGa_{1-x})_2O_3$ film. In conjunction with energy dispersive spectroscopy, the striations are identified as regions of high Al content. In the films that were grown on c-plane sapphire, the high Al content striations run parallel to the (-201) surface. However, in the case of the 6° miscut sapphire substrates, the high Al content striations are oriented about 8-10° from the surface. In addition, the average period of the striations is smaller with higher Al content ranging from 25 to 7 nm periods for $x = 0.04$ and $x = 0.3$ respectively.

XRD (-401) pole figures were measured for $(Al_xGa_{1-x})_2O_3$ films (with $0<x<0.3$) and a commercially available (-201) β-Ga_2O_3 substrate as a reference. XRD (-401) pole figure for the (-201) β-Ga_2O_3 reference substrate shows both (-401) at χ = ~23° and (-400), at χ = ~50° (the 2θ angle difference is less than 0.5°) with no symmetry. However, the pole figures from the $(Al_xGa_{1-x})_2O_3$ thin films grown on sapphire ($0<x<0.3$) all show six-fold symmetry for both (-401) and (-400). We believe the six-fold symmetry is a result of three sets of twins (120° away from each other), plus the existence of anti-parallel domains (0° and 180° pairs). On the other hand, additional 12 spots at χ = ~58° were observed in the $(Al_xGa_{1-x})_2O_3$ films on sapphire. These do not correspond to any planes with (-201) surface orientation, suggesting grains with different orientation exist. We speculate that the anisotropy of the monoclinic structures, the surface energy differences associated with the miscut substrate, and step edge features impact the formation of the composition striations.

5:00pm **TM-MoA-14 Plasmon-phonon Coupling in Electrostatically Gated *β*-Ga_2O_3 Films with Mobility Exceeding 200 $cm^2V^{-1}s^{-1}$***,* *A. Rajapitamahuni, A. Manjeshwar,* University of Minnesota, USA*; A. Kumar, A. Datta,* University at Buffalo*; P. Ranga,* University of California Santa Barbara*; L. Thoutam,* SR University, Warangal, India*; S. Krishnamoorthy,* University of California Santa Barbara*;* ***Uttam Singisetti****,* University at Buffalo*; B. Jalan,* University of Minnesota, USA

Monoclinic β-Ga_2O_3, an ultrawide-bandgap semiconductor, has seen enormous activity in recent years. However, the fundamental study of the plasmon-phonon coupling that dictates electron transport properties has not been possible due to the difficulty in achieving higher carrier density (without introducing chemical disorder). In this talk, we present a highly reversible, electrostatic doping of β-Ga_2O_3 films with tunable carrier

densities using ion-gel-gated electrical double layer transistor configuration. Combining temperature dependent Hall effect measurements, transport modeling and comprehensive mobility calculations using ab-initio based electron-phonon scattering rates, we demonstrate an increase in the room-temperature mobility to 201 $cm^2V^{-1}s^{-1}$ followed by a surprising decrease with an increasing carrier density is due to the plasmon-phonon coupling. The modeling and experimental data further reveal an important “anti-screening” (of electron-phonon interaction) effect arising from dynamic screening from the hybrid plasmon-phonon modes. Our calculations show that a significantly higher room-temperature mobilities of 300 $cm^2V^{-1}s^{-1}$ is possible if high electron densities (> 10^{20} cm-3) with plasmon energies surpassing highest energy LO mode can be realized. As Ga_2O_3 and other polar semiconductors play an important role in several device applications, the fundamental understanding of the plasmon-phonon coupling can pave the way to enhance the mobility by harnessing the dynamic screening of the electron-phonon interactions.

Advanced Characterization Techniques
Room Jefferson 1 & Atrium - Session AC-MoP
Advanced Characterization Techniques Poster Session

AC-MoP-1 Advanced Defect Characterization in b-Ga_2O_3 Without the Arrhenius Plot, *J. Li,* NCKU, Taiwan*;* ***Adam Neal****, S. Mou,* Air Force Research Laboratory, Materials and Manufacturing Directorate, USA*; M. Wong,* University of Massachusetts Lowell

Defect is one of the issues that limit the present performance of β-Ga_2O_3 devices. For example, several defects have been observed at 0.6, 0.8. and 1.1 eV below the conduction band edge of β-Ga_2O_3, which are considered to affect doping compensation, leakage current, and threshold stability in transistors. Conventional detection of β-Ga_2O_3 defects (in various forms such as Hall, conductivity, admittance spectroscopy, and deep-level transient spectroscopy (DLTS)) is accomplished by inspecting the electrical charge response, which is based on the Arrhenius behavior of the carrier emission rate from a defect determined by the activation energy E_a and the attempt-to-escape frequency ν_0. All thermally activated electrical charge response measurements are conventionally analyzed by the Arrhenius plot procedure, where one fits the Arrhenius plot of ln(ν) versus T^{-1} to a line and extract E_a from the slope and ν_0 from theintercept. Improvement of the measurement expediency for extracting E_a and ν_0 is desirable to understanding their physiochemical origins and devising mitigation strategies in β-Ga_2O_3 material and device engineering.

We investigate a ~0.8 eV defect in β-Ga_2O_3 using a technique that offers substantial improvement over the conventional DLTS technique, specifically in the analytical processing of electrical signal and the extraction of E_a and ν_0. The technique bypasses both the rate-window treatment and the Arrhenius plot. First, only the raw capacitance transients in the time domain are needed, which can be readily acquired by general-purpose instruments such as impedance analyzers and lock-in amplifiers. Next, the capacitance transients are projected between the temperature and time domains, as well as to the E_a and ν_0 domains. Extraction of E_a and ν_0 is accomplished by matching the projected and experimental capacitance transients to each other. The efficient utilization of information from the 2D temperature-time domain allows operation in a smaller temperature/voltage range and extraction of the temperature and electric-field dependence of E_a and ν_0.

AC-MoP-2 Infrared-Active Phonon Modes and Static Dielectric Constants of Orthorhombic $LiGaO_2$, ***Teresa Gramer****, M. Stokey, R. Korlacki, M. Schubert,* University of Nebraska - Lincoln

Li_2O-Ga_2O_3 is an oxide system of broader interest. $LiGaO_2$ (LGO) and multiple phases of Ga_2O_3 (GO) are ultra-wide bandgap metal oxides for future electronic and optoelectronic applications [1], and both LGO, which is orthorhombic, and the orthorhombic phase of GO are expected to be piezoelectric due to the lack of inversion symmetry [1]. While both GO and LGO have recently been identified to most likely trap holes which makes the achievement of sufficient p-type conductivity difficult [2], LGO is particularly promising as a substrate for heteroepitaxial growth of GaN due to very small lattice mismatch (<1%), and a composite LGO/β-GO substrate has also been demonstrated [3]. Here, we provide a thorough study of the fundamental optical and phonon mode properties of high-quality single-crystals of LGO using generalized spectroscopic ellipsometry in combination with hybrid-level density functional theory calculations to investigate the optical properties in the mid- to far-infrared spectral range. From this, all 33 infrared-active pairs of transverse and longitudinal optical phonon modes are observed. We derive the anisotropic midband gap indices of refraction and static dielectric constants.

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AC-MoP-3 Spectroscopic Ellipsometry Optical Analysis of Zinc Gallate at Elevated Temperatures*,* ***Emma Williams,*** University of Nebraska-Lincoln, USA*; M. Hilfiker, U. Kilic, Y. Traouli, N. Koeppe, J. Rivera, A. Abakar, M. Stokey, R. Korlacki,* University of Nebraska - Lincoln*; Z. Galazka,* Leibniz-Institut für Kristallzüchtung, Germany*; M. Schubert,* University of Nebraska - Lincoln

Zinc gallate ($ZnGa_2O_4$) is shown to be a promising alternative to gallium oxide. This is due to the material's larger bandgap of 5.27(3) eV, compared to that of β-Ga_2O_3 (5.04 eV), which is linked to a higher Baliga's figure of merit. [1,2] $ZnGa_2O_4$ also contains an isotropic structure, which is advantageous compared to both the monoclinic β-phase and uniaxial *α*-phase of Ga_2O_3 in simplifying device design. [2,5] Additionally, $ZnGa_2O_4$ growth has rapidly developed to where bulk single crystals can be melt-grown with controllable n-type conductivity. [4]

In this work, the optical properties of $ZnGa_2O_4$ are modeled using a spectroscopic ellipsometry approach at temperatures between 22°C and 600°C, where material properties drastically change in elevated temperatures. At each 50°C interval a Cauchy dispersion equation is applied to the transparent region of the data where the refractive index and high-frequency refractive index is derived. Furthermore, a critical point model is implemented across the spectral range of 1 eV to 6.5 eV. This allows for the determination of the bandgap, which is found to red-shift linearly with temperature with a slope of -0.72(4) meV K^{-1}, resulting from the thermal expansion of the lattice. [3] The linear decrease in the bandgap energy when exposed to increasing elevated temperatures is in congruence with behavior shown by common wide bandgap metal oxides. In particular, the reduction of bandgap width as a function of temperature is comparable to that of the ultrawide bandgap material β-Ga_2O_3, further justifying $ZnGa_2O_4$ as a suitable high-power device material. [2,3]

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AC-MoP-4 The Electron Spin Hamiltonian for Fe^{3+} in Monoclinic β-Ga_2O_3*, S. Richter,* Lund University, Sweden*; S. Knight, P. Kühne,* Linköping University, Sweden*;* ***Mathias Schubert,*** University of Nebraska - Lincoln*; V. Darakchieva,* Lund University, Sweden

Large interest in Ga_2O_3 originates from the possibility to build devices with high breakdown voltage. Understanding electronic defects is essential to utilize the material. As β-Ga_2O_3 is monoclinic, the effect of the low symmetry needs to be studied. Electron (paramagnetic) spin resonance (EPR) spectroscopy gives access to local site symmetry of spin-carrying defects. Deploying THz ellipsometry [1], we can measure high-field EPR at arbitrary variable frequency by reflection a free beam [2]. This allows true distinction of anisotropic g-factor and zero-field spin splitting, and hence examining the local site symmetry of electronic defects.

Iron incorporated on gallium sites can act as compensating acceptor and facilitate semi-insulating material. Here, we investigate the spin Hamiltonian of the neutral Fe^{3+} state with spin s=5/2. It is characterized by large zero-field splitting that differs for Fe on octahedral Ga_{ii} site (preferential) and Fe on tetrahedral Ga_i site. Different, partially incorrect, reports exist about the nature of the spin Hamiltonian [3,4]. In contrast to standard EPR measurements at X or Q band with limited access to allowed spin transitions, we obtain EPR scans in the frequency range 110-170GHz at magnetic field between 3 and 7T that capture all five resonances for each Fe site at the same time. Modeling the spin Hamiltonian reveals a slight anisotropy of the g-factor and shows that zero-field splitting up to fourth order is relevant. We will discuss how the monoclinic s=5/2 spin Hamiltonian differs from orthorhombic and/or s=3/2 approximations.

[1] P. Kühne *et al.*, IEEE Trans. Terahertz Sci. Technol. **8**(3), 257 (2018).
[2] S. Schubert *et al.*, Appl. Phys Lett. **120**, 102101 (2022).
[3] R. Büscher *et al.*, Z. Naturforsch. **42a**, 67 (1987).
[4] M. L. Meil'man, Sov. Phys. Sol. State **11**(6), 1403 (1969).

The supplemental material features exemplary experimental data and the form of the spin Hamiltonian.

AC-MoP-5 Characterization of (010) β-Ga_2O_3 to Support Fabrication, Wafer Size Scaleup, and Epi Development, ***David Snyder,*** Penn State Applied Research Laboratory

Efficient wafer size scaleup of quality (010) β-Ga_2O_3 substrates and epi development require extensive materials characterization. Over the past two years, the Applied Research Laboratory (ARL) Electronic Materials and Devices Department (EMDD) has partnered with Northrop Grumman's SYNOPTICS division in support of the Air Force Research Laboratory (AFRL)'s initiative to produce 2-inch epi-ready (010) β-Ga_2O_3 substrates via the Czochralski (Cz) method. As part of this effort, ARL has developed a multitude of techniques specifically for characterizing β-Ga_2O_3 substrates at various stages of processing. In this poster, we highlight these techniques and describe the rapid feedback loop that ARL enables between those working on crystal growth, substrate fabrication, epi growth, and device processing within the expanding β-Ga_2O_3 community.

This poster covers defect mapping and identification, surface metrology, and x-ray characterization. Each of these areas provide essential information about the quality of β-Ga_2O_3 substrates for subsequent epi growth and ultimately device fabrication. We show how etch pit analysis is used to automatically map defects in up to 2-inch wafers in conjunction with the focused ion beam (FIB) approach to prepare cross-sections for imaging the defect structures, including nanopipes. White light interferometry/profilometry and atomic force microscopy (AFM) provide three-dimensional topography information about the wafers, i.e., after polishing, thermal annealing, or free etching. This poster also describes our method for in-situ high-resolution x-ray characterization during fabrication in which a decrease in full-width at half-maximum (FWHM) was correlated with removal amount to optimize β-Ga_2O_3 polishing. Finally, we discuss how x-ray characterization provides information about curvature and substrate/epi layer quality with grazing incidence x-ray diffraction (GIXRD) being utilized to provide extremely surface-sensitive monitoring.

AC-MoP-6 Photoluminescence Spectroscopy of Cr^{3+} in β-Ga_2O_3 and $(Al_{0.1}Ga_{0.9})_2O_3$, ***Cassandra Remple,*** *J. Jesenovec, B. Dutton, J. McCloy, M. McCluskey,* Washington State University

Alloying β-Ga_2O_3 with Al_2O_3 to create $(Al_xGa_{1-x})_2O_3$ enables ultra-wide band gap material deep into the UV. Here, photoluminescence (PL) spectra of Cr^{3+} dopant is compared between monoclinic single crystals β-Ga_2O_3, and 10 mol.% Al_2O_3 alloyed with β-Ga_2O_3, denoted β-$(Al_{0.1}Ga_{0.9})_2O_3$ or AGO. Temperature dependent PL properties were studied for Cr^{3+} in AGO and β-Ga_2O_3 from 285 to 16 K. For β-Ga_2O_3at room temperature, the red-line emission doublet R_1 and R_2 occurs at 696 nm (1.78 eV) and 690 nm (1.80 eV) respectively along with a broad emission band at 709 nm (1.75 eV). For both AGO and β-Ga_2O_3 the R_1 line increases in intensity with decreasing temperature. This can be explained by the thermal depopulation effect of the R_1 state, which occurs with increasing temperature. The R_1 and R_2 lines of both materials were observed to blue-shift with decreasing temperature. Additional emission lines emerge at lower temperatures, with β-Ga_2O_3 showing more peaks than AGO. R_1 and R_2 peak parameters such as energy, intensity, width, and splitting were studied as a function of temperature, with significant differences between the two materials.

AC-MoP-7 Surface Relaxation and Rumpling of Sn Doped B-ga2o3(010), ***Nick Barrett,*** CEA Saclay, France*; A. Pancotti,* Universidade Federal de Jataí, Brazil*; T. Back,* AFRL*; W. Hamouda, M. Laccheb, C. Lubin, A. Boucly,* CEA Saclay, France*; P. Soukiassian,* Université Paris-Saclay, France*; J. Boeckl, D. Dorsey, S. Mou, T. Asel,* AFRL*; G. Geneste,* CEA, France

We have used X-ray Photoelectron Diffraction (XPD), low-energy electron diffraction (LEED), atomic force microscopy (AFM) and X-ray photoelectron spectroscopy (XPS) to determine the surface structure, chemistry and interplanar relaxation and rumpling in single crystal, Sn-doped b-Ga_2O_3 (010). XPD is a powerful technique, which combines information on local chemistry and atomic structure. By measuring the angular anisotropy of core level intensity one can, by comparison with simulations, deduce the local atomic and chemical environment around each type of emitting atom. The XPS measurements show typical spectra for stoichiometric Ga_2O_3(010). Annealing at 823 K yielded a well-ordered surface with sharp (1x1) low-energy electron diffraction (LEED) pattern. AFM shows unique surface termination with root mean square roughness of 0.1-0.15 nm. The XPD measurements were performed using a laboratory based setup with a monochromatic Al Ka (1486.7 eV) source and a high precision angular manipulator capable of scanning both polar (q) and azimuthal (f) angles. The XPD patterns collected for the Ga $2p_{3/2}$ and O 1s emission. Surface interlayer relaxation up to 8% of the bulk interplanar distance and 0.11–0.14 Å rumpling are observed at the β-Ga_2O_3(010) surface. At the surface, the oxygen atoms shift toward the vacuum with respect to the gallium atoms. The rumpling decreases to zero and and the interplanar distance reaches the bulk value of 1.52 Å by the sixth atomic layer. The surface structure agrees with that predicted by first-principles density functional theory calculations which, in addition, suggest a significant band gap narrowing of ≈1 eV in the surface layer, due to surface states spatially localized on surface oxygen atoms of O_{II} type.

A. Pancotti *et al. Phys. Rev. B***102**, 245306 (2020)

AC-MoP-8 Probing Vacancies and Hydrogen Related Defects in β-Ga_2O_3 with Positrons and FTIR, ***Corey Halverson,*** *M. Weber, J. Jesenovec, B. Dutton, C. Remple, M. McCluskey, J. McCloy,* Washington State University

β-Ga_2O_3 is a promising material for power electronics. Ubiquitous hydrogen and vacancies strongly influence the electronic properties of these materials. Methods to detect and characterize them are desirable. Fourier Transform Infrared Spectroscopy (FTIR) and Positron Annihilation Spectroscopies (PAS) both have been use with success. Here, they are applied to investigate the hydrogen content in gallium vacancies particularly in the top 6 micrometers below the surface. A Czochralski grown bulk single crystal is explored before and after repeated annealing in vacuum with the main goal to remove hydrogen from the sample. The hydrogen reduction method was first applied with success on single crystal ZnO samples. β-Ga_2O_3 is sealed in an evacuated hydrogen-depleted quartz tube together with thin foils of titanium. Before sealing the ampoule, the quartz and the titanium are heated repeatedly to drive out trapped hydrogen. Then β-Ga_2O_3 is annealed at 850C to 900C for up to 8 days while maintaining the Ti-foil at the other end of the ampoule at room temperature. Depth resolved PAS Doppler broadening data reveal significant reduction in the effective positron diffusion length and small changes in the vacancy sensitive width of the annihilation line (S-parameter). These changes reversed by subsequent annealing in hydrogen. The positron data will be presented and correlated with bulk FTIR measurements on the same sample. This work generously supported by the Air Force Office of Scientific Research under award number FA9550-18-1-0507 monitored by Dr. Ali Sayir.

AC-MoP-9 Evolution of Anisotropy and Order of Band-to-Band Transitions, Excitons, Phonons, Static and High Frequency Dielectric Constants Including Strain Dependencies in Alpha and Beta Phase $(Al_xGa_{1-x})_2O_3$, ***Megan Stokey,*** University of Nebraska-Lincoln*; R. Korlacki, M. Hilfiker, T. Gramer,* University of Nebraska - Lincoln*; J. Knudtson,* University of Nebraska-Lincoln*; S. Richter,* Lund University, Sweden*; S. Knight,* Linköping University, Sweden*; A. Mock,* Weber State University*; A. Mauze, Y. Zhang, J. Speck,* University of California Santa Barbara*; R. Jinno, Y. Cho, H. Xing, D. Jena,* Cornell University*; Y. Oshima,* National Institute for Materials Science, Japan*; E. Ahmadi,* University of Michigan*; V. Darakchieva,* Lund University, Sweden*; M. Schubert,* University of Nebraska - Lincoln

The rhombohedral alpha and monoclinic beta phases of gallium oxide both make promising candidates for ultra-wide bandgap semiconductor technology. Of particular interest are alloyed films and the evolution of anisotropic optical properties with respect to both alloy composition and strain induced effects. Here, we study alpha and beta phase $(Al_xGa_{1-x})_2O_3$ via a combined density functional theory and generalized spectroscopic ellipsometry approach across a range of alloying. Infrared-active phonon properties, static dielectric constants and midband gap indices of refraction are quantified.[1,2,3] Strain and alloying effects are shown and compared to previous theoretical works.[4] Band-to-band transitions, excitons, and high-frequency dielectric constants are also investigated in the visible to vacuum-ultra-violet (VUV) spectral range.[5,6,7,8] We identify a switch in band order where the lowest band-to-band transition occurs with polarization along the ordinary plane in α-$Ga_{-2}O_{-3}$ whereas for α-$Al_{-2}O_3$ the lowest transition occurs with polarization in the extraordinary direction. With this, we present the most comprehensive picture of optical properties' evolution along composition and strain currently available.

[1] M. Stokey, *et al.,* Phys. Rev. Materials 6, 014601 (2022)

[2] M. Stokey, *et al.,* Appl. Phys. Lett. 120, 112202 (2022)

[3] The influence of strain and composition on the infrared active phonons in epitaxial β-(AlxGa1-x)2O3 deposited onto (010) β-Ga2O3; M. Stokey, *et al.*, *In Preparation*

[4] R. Korlacki, *et al*., Rev. B 102, 180101(R) (2020)

[5] M. Hilfiker, *et al.,* Appl. Phys. Lett. 118, 062103 (2021)

[6]Anisotropic dielectric function, direction dependent bandgap energy, band order, and indirect to direct gap cross over in α-(AlxGa1-x)2O3 (0≤x≤1); M. Hilfiker, *et al.,* Appl. Phys. Lett. XX, XX (2022)

[7] M. Hilfiker, *et al.,* Appl. Phys. Lett. 119, 092103 (2021)

[8] M. Hilfiker, *et al.,* Phys. Lett. 114, 231901 (2019)

AC-MoP-10 Photoluminescence Mapping of Gallium Oxide and Aluminum Gallium Oxide Epitaxial Films*, **Jacqueline Cooke**, P. Ranga,* University of Utah*; J. Jesenovec, J. McCloy,* Washington State University*; S. Krishnamoorthy,* University of California at Santa Barbara*; M. Scarpulla, B. Sensale-Rodriguez,* University of Utah

The mechanisms generating photoluminescence (PL) emissions from gallium oxide (Ga_2O_3) and aluminum gallium oxide (AGO) have been under intense scrutiny. In general, spectrally-resolved PL is used to characterize the defects leading to radiative recombination processes within a specific material. In this regard, the PL spectra for β-Ga_2O_3 has generally been deconvoluted in three emission bands: UV, blue, and green. So far, the intense debate in defining the defects and phenomenological explanations of electronic processes that cause Ga_2O_3 and AGO emissions have only explored point defects as the potential source for the PL emission leaving out whether extended defects could affect PL. Because of the strong electron phonon coupling, emission peak shapes from any defect are expected to be very broad and not have a simple functional peak shape; these attributes make it challenging to fit spectra uniquely. Because of this, there is little chance of directly assigning PL spectral features unambiguously to specific β-Ga_2O_3 point defects from PL alone.

Here, a systematic PL study on multiple series of β-Ga_2O_3 and AGO epitaxial thin films and bulk single crystals is performed. Spectrally-resolved PL, PL intensity mapping, scanning electron microscopy (SEM), atomic force microscopy (AFM), and transmission electron microscopy (TEM) were used along with literature to show that extended structural defects largely determine the PL emission from many samples of β-Ga_2O_3 and AGO. Homogeneous films with no extended defects or stacking faults and bulk crystals yield PL emission with a dominant UV peak, while samples of lesser crystalline quality exhibiting stacking faults, rotation domain boundaries, and other such extended defects do not exhibit a UV emission but rather exhibit blue.

Si-doped homoepitaxial (010) β-Ga_2O_3 samples yield homogeneous crystalline films with a low density of extended defects and an unshifting dominant UV emission in PL. A bulk (-201) β-Ga_2O_3 sample shows a dominant UV emission while heteroepitaxial and homoepitaxial (-201) β-Ga_2O_3 films show dominant blue PL emission (due to the films' poor quality as seen in PL mapping, AFM and SEM). An AGO series shows consistent blue centered PL for AGO grown on both sapphire and β-Ga_2O_3 (also due to the films' poor quality as seen in TEM, PL mapping, AFM and SEM). Lastly, an improved (reduced number of extended defects) 10% AGO film grown on (010) bulk β-Ga_2O_3 show a shift in the PL spectrum with a now UV dominant emission. PL mapping shows that areas of extended defects emit blue PL while the crystal film emits UV PL within the sample.

AC-MoP-12 Non-Destructive Characterization of Annealed Si-Implanted Thin Film β-Ga_2O_3*, **Aine Connolly**, K. Gann,* Cornell University*; S. Tetlak,* Air Force Research Laboratory*; V. Protasenko,* Cornell University*; M. Slocum, S. Mou,* Air Force Research Laboratory*; M. Thompson,* Cornell University

Selective doping by ion implantation is critical for small-scale device fabrication in wide-bandgap materials such as β-Ga_2O_3, requiring understanding of both lattice damage due to implantation and subsequent lattice recovery during thermal annealing. Carrier activation, mobility, and diffusion are known to be critically coupled to annealing temperature, time and ambient as well as intrinsic and extrinsic film properties. Electrical measurements provide one measure of annealing behavior, but are limited due to the need for direct metal contacts, the intrinsic spatial averaging, and the inability to directly measure lattice recovery or observe associated defects. To address these limitations, we present Raman spectroscopy and photoluminescence (PL) measurements of β-Ga_2O_3 implanted and annealed samples, evaluating their ability to local carrier activation and lattice recovery non-destructively.

Recent studies of bulk doped β-Ga_2O_3 [1] have identified additional Raman peaks in samples with carrier concentrations above the Mott criterion. To determine if these peaks are directly linked to carrier activation, we examined a wide range of Si-implanted ($5x10^{19}$ cm^{-3}) and annealed samples using a laterally localized Raman probe. A peak at 285 cm^{-1} was observed above the noise floor in several samples, with the intensity increasingly linearly with sheet carrier density (N_s). The effect of the lattice quality (recovery) on the relative intensities of other Raman peaks was also analyzed.

Previous β-Ga_2O_3 studies suggest that an increase in activated dopants decreases the total PL, due to the higher defect density and the resultant probability of electrons reaching non-radiative recombination centers [2]. PL behavior of the Si-implanted samples was thus measured as a function of lattice recovery with (N_2 ambient) and without (O_2 ambient) carrier activation. The Pl signal decreased dramatically after implantation, with partial recovery after thermal anneals and lattice damage recovery. Negative correlation was observed between the PL intensity and carrier activation. Correlations between PL and cathodoluminescence were also measured.

[1] Fiedler, A., Ramsteiner, M., Galazka, Z., and K. Irmscher. Raman scattering in heavily donor doped B-Ga2O3. *Appl. Phys. Lett.* 117, 152107 (2020)

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Dielectric Interfaces
Room Jefferson 1 & Atrium - Session DI-MoP
Dielectric Interfaces Poster Session

DI-MoP-1 Band Offsets of MOCVD Grown β-(Al0.21Ga0.79)2O3/β-Ga2O3 (010) Heterojunctions*, T. Morgan, J. Rudie, M. Zamani-Alavijeh, A. Kuchuk,* University of Arkansas*; N. Orishchin, F. Alema,* Agnitron Technology Incorporated*; A. Osinsky,* Agnitron Technology Incorporated, United States Minor Outlying Islands (the)*; R. Sleezer,* Minnesota State University at Mankato*; G. Salamo,* University of Arkansas, United States Minor Outlying Islands (the)*; **Morgan Ware**,* University of Arkansas

Recently, high quality alloys of β-$(Al_xGa_{1-x})_2O_3$, have been grown demonstrating excellent properties for use in high power, high frequency, and high voltage systems and devices such as wireless communication, satellite electronics, and electrified transportation.A natural step to follow the formation and study of these alloys is the study of their thin film heterostructures and subsequent devices. In order to support this, the heterostructure band offsets must be known well enough to model device performances. These values will vary slightly with crystal direction, i.e., the growth plane, as will the optimized growth conditions and film quality. Theoretical predictions for the monoclinic (β) aluminum oxide/gallium oxide interface predict a type-II interface with a maximum VBO value of 0.33 eV for Al_2O_3.

The presented study focuses on the stable (010) heterointerface. Several films of high quality β-$(Al_{0.21}Ga_{0.79})_2O_3$ were grown by metal organic chemical vapor deposition on bulk (010) oriented β-Ga_2O_3.The indirect bandgap of the β-$(Al_{0.21}Ga_{0.79})_2O_3$ was determined through optical transmission to be 4.69 eV with a direct transition of 5.37 eV, while β-Ga_2O_3 was confirmed to have an indirect bandgap of 4.52 eV with a direct transition of 4.94 eV. Theoretical calculations for this interface predict a type-II band alignment with a small VBO of only 0.08 eV and a conduction band offset (CBO) of 0.4 eV for a fully strained, 21% Al film on (010) β-Ga_2O_3.Experimentally, in the presented work, the band offsets for this β-$(Al_{0.21}Ga_{0.79})_2O_3$/β-$Ga_2O_3$ (010) heterojunction were then measured using x-ray photoelectron spectroscopy.The resulting band alignment was determined to be of type II with the valence and conduction band edges of the β-$(Al_{0.21}Ga_{0.79})_2O_3$ being -0.26eV and 0.43 eV, respectively above those of the β-Ga_2O_3 (010). These values can now be used to help better design and predict the performance of β-$(Al_xGa_{1-x})_2O_3$ heterojunction-based devices.

DI-MoP-2 Optimization of MOCVD Grown In-situ Dielectrics for β-Ga_2O_3*, G. Wang,* University of Wisconsin - Madison*; F. Alema,* Agnitron Technology Inc.*; J. Chen,* University of Wisconsin - Madison*; A. Osinsky,* Agnitron Technology Inc.*; C. Gupta,* University of Wisconsin-Madison*; **Shubhra Pasayat**,* University of Wisconsin - Madison

For ultra-WBG semiconductors, the development of dielectrics that can hold a much larger electric field demands high-quality films free of buried charges and traps. For Ga_2O_3, Al_2O_3 has proven to be a promising gate dielectric[1], typically grown using ALD at ~250 °C utilizing trimethylaluminum (TMA) and H_2O as precursors. Recently, MOCVD grown Al_2O_3 on β-Ga_2O_3 was demonstrated [2], using TMA and O_2 precursors but grown at 600 °C, with Ar carrier gas. In this prior work, a lower fixed charge of 2 x 10^{12} cm^{-2} compared to 3.6 x 10^{12} cm^{-2} in ALD Al_2O_3 on β-Ga_2O_3 was observed[2]. Higher growth temperatures lead to efficient pyrolysis of metal-organic sources like TMA, resulting in lower unintentional C content. The

presence of C leads to donor and acceptor level creation, hence low C content allow lower leakage, higher V_{BR}, and reduced interface-state densities of MOS devices[3]. In addition, dielectrics grown within the MOCVD reactor (in-situ), as opposed to ALD chamber (ex-situ), avoid a regrowth interface, lowering interface-state densities[4]. Using triethylaluminum (TEA) instead of TMA, may improve the quality of in-situ Al_2O_3 as the ethyl radical is readily desorbed from the growth surface by the β-hydride elimination of ethene, reducing the C in Al_2O_3[5].

In this work, the Al_2O_3 dielectric growth using TEA and O_2 precursors in a 7x2" MOCVD reactor with close injection showerhead is reported, grown at 500-900°C on Sn-doped Ga_2O_3 and Si substrates. A constant TEA flow of 4.75 µmol/min was introduced into the reactor using Ar and N_2 carrier gases while the O_2 flow was varied as 100, 400, and 700 sccm, resulting in growth rates (GR) of 0.6, 1.4, and 1.7 nm/min, respectively. Compared to 1.2 nm/min GR reported using TMA precursor in an R&D MOCVD reactor [2], these GR demonstrate the prospect of TEA as a potential alternative to further improve the in-situ Al_2O_3 dielectric quality. The influence of N_2 as the sole carrier gas was also studied by introducing a TEA flow of ~3.4 µmol/min at an O_2 flow of 400 sccm, resulting in a 7x lower thickness variation across a 2" wafer without affecting the GR. The C content in Al_2O_3 resulting from TEA and TMA precursors, the use of alternate O precursors like N_2O, the D_{it} and V_{BR} comparison with other in-situ dielectrics like SiO_2 or $AlSiO_x$ will be quantified using CV and IV measurements on MOSCAP structures and reported at the conference.

1. K. D. Chabak *et al.* APL, vol. 109, no. 21, 2016 2. S. Roy *et al.* AEM, vol. 7, no. 11, 2021 3. M. Uenuma *et al.* AIP Adv., vol. 8, no. 10, 2018 4. S. H. Chan *et al.* APEX, vol. 11, no. 4, 2018 5. A. C. Jones, Chem. Soc. Rev. vol. 26, 1997

Electronic and Photonic Devices, Circuits and Applications
Room Jefferson 1 & Atrium - Session EP-MoP

Electronic and Photonic Devices, Circuits and Applications Poster Session

EP-MoP-2 Gate Effects of Channel and Sheet Resistance in β-Ga_2O_3 Field-Effect Transistors using the TLM Method,
Ory Maimon, Department of Electrical Engineering, George Mason University*; N. Moser,* Air Force Research Laboratory, Sensors Directorate*; K. Liddy, A. Green, K. Chabak,* Air Force Research Laboratory, Sensors Directorate, USA*; C. Richter, K. Cheung, S. Pookpanratana,* Nanoscale Device and Characterization Division, National Institute of Standards and Technology*; Q. Li,* Department of Electrical Engineering, George Mason University

Beta Gallium Oxide (β-Ga_2O_3) is a rapidly developing semiconductor for high power electronic devices with promising advantages. Accurate characterization of the resistances in β-Ga_2O_3 field-effect transistors (FET) are critical to understand and model these devices. Here, we report on extracting contact, channel, and sheet resistances from planar, depletion-mode β-Ga_2O_3 FETs using the transfer length method (TLM). The results are analyzed in comparison with conventional TLM structures fabricated on the same wafer. The β-Ga_2O_3 FETs are composed of a 50-nm Si-doped epi-layer with a target concentration of 2.4×10^{18} cm^{-3} fabricated on a (010) semi-insulating β-Ga_2O_3 substrate. Aluminum oxide (Al_2O_3, 20 nm) was used as the gate dielectric and the gate length (L_G) remained constant at 1.94 µm, while the source-drain spacing (L_{SD}) varied as 3µm, 8 µm, and 13 µm. No back contact was used due to the semi-insulating substrate. Transfer characteristic measurements were taken at room temperature and low drain-source voltage (V_{DS}) of 0.01 V to suppress drain effects on the threshold voltage (V_{TH}), about -4 V, for devices at different L_{SD} spacing.

When compared to the TLM structures, we observe a decrease in extracted sheet resistance (R_{sh}), and channel sheet resistance (R_{ch}) as the channel turns on with increasing gate-source voltage (V_{GS}). The contact resistance (R_C) is assumed to be constant, and is found to be 27.7 Ω mm at a V_{GS} of 0 V. From a V_{GS} of -3 V to 3 V (off to on state), R_{sh} quickly decreases from 90.4 kΩ sq^{-1} and appears to plateau at 28.2 kΩ sq^{-1}. We saw a similar trend for R_{ch}, which decreased from 288 kΩ sq^{-1} to 7.66 kΩ sq^{-1}. From the channel sheet resistance, we can find an accurate field-effect mobility after removing the parasitic resistances. A FET with an L_{SD} of 3µm was found to have a field-effect mobility of 61 cm^2 V^{-1} s^{-1} at a V_{GS} of 3 V. This work indicates that the channel resistance can be accurately extracted by applying the TLM method to FETs, and further helps understand β-Ga_2O_3 gate effects on transistor performance.

EP-MoP-3 Lateral β-Ga_2O_3 Schottky Barrier Diodes With Interdigitated Contacts,
Jeremiah Williams, Air Force Research Laboratory, Sensors Directorate*; A. Arias-Purdue,* Teledyne*; K. Liddy, A. Green,* Air Force Research Laboratory, Sensors Directorate*; D. Dryden, N. Sepelak,* KBR*; K. Singh,* Air Force Research Laboratory, Sensors Directorate*; F. Alema, A. Osinsky,* Agnitron Technology*; A. Islam, N. Moser, K. Chabak,* Air Force Research Laboratory, Sensors Directorate

This work characterizes a lateral β-Ga_2O_3 Schottky barrier diode (SBD) with an interdigitated contact design fabricated using a homoepitaxial thin-film. This SBD design can be monolithically integrated into RF power switching circuits with standard lateral FET processing. This technique avoids complex fabrication and losses from heterogeneous integration while maintaining the fast switching capabilities of a thin, lateral channel. Prior literature has shown impressive performance from vertical SBDs [1] and lateral devices on non-native substrates [2], but lateral SBDs on homoepitaxial β-Ga_2O_3 thin-films are not well explored. To the authors' knowledge, this is the first demonstration of such a SBD design in β-Ga_2O_3.

The β-Ga_2O_3 epitaxial layer is grown by MOCVD with a target thickness of 65 nm. Hall effect measurements indicate Si doping of 3.347e17 cm^{-3}, carrier mobility of 86.5 cm^2/V-s, and a sheet resistance of 33.15 kΩ/sq. A surface RMS roughness of 0.839 nm is measured by AFM. Mesa isolation is achieved with a BCl_3 ICP etch. Ohmic contacts are formed by Si ion implantation and a metal stack of Ti/Al/Ni/Au (25/120/50/50 nm) annealed at 470°C. Implant carrier concentration is measured at 5.976×10^{19} cm^{-3}. Evaporated Pt/Au (20/380 nm) forms the Schottky contact. The first passivation layer is 30 nm of Al_2O_3 deposited by ALD patterned with BOE. Next, a metal interconnect layer of Ir/Au (10/380 nm) is deposited. Final passivation is ~85 nm of Al_2O_3 by ALD pattered with a CF_4 RIE etch. All metal is pattered by photoresist lift off.

The diode features four 4x50 µm anode fingers interdigitated with five 8x50 µm cathode fingers. The anode-cathode spacing is 5 µm. The Pt-Ga_2O_3 barrier height is extracted from temperature dependent J-V measurements to be 1.742 eV. Fitting to forward bias J-V measurements shows an ideality factor of 2.246 and a build-in voltage of 1.963 V. The diode has a breakdown voltage (V_{bk}) of 784 V and a specific on-resistance ($R_{on,sp}$) of 9.133 Ω-cm^2, normalized to the current carrying region between contacts. This yields a power figure of merit (PFOM) of 67.3 MW/cm^2. We attribute the poor ideality to the highly resistive epitaxy and the degraded interface caused by the relatively rough surface. This device is competitive with published lateral SBD results, and establishes a baseline to enable further development of β-Ga_2O_3 RF power switching circuits with a streamlined, monolithic fabrication process.

[1] S. Roy *el al.*, *IEEE Electron Device Lett.*, **34**, 8, (2021).

[2] Z. Hu *et al.*, *IEEE Electron Device Lett.*, **39**, 10, (2018).

EP-MoP-4 Optimized Annealing for Activation of Implanted Si in β-Ga2O3,
Katie Gann, *J. McCandless,* Cornell University*; T. Asel, S. Tetlak,* Air Force Research Laboratory*; D. Jena, M. Thompson,* Cornell University

Ion implantation of β-Ga_2O_3 will be critical for low resistance contacts and advanced device structures. Literature suggests good activation of Si implants after annealing under N_2, but reversible deactivation of carriers under O_2-rich annealing. However, there have been no significant studies establishing annealing behavior as a function of time, temperature, and controlled gas ambients. Unintentionally doped (UID) β-Ga_2O_3 films, grown by plasma assisted molecular beam epitaxy on Fe-doped semi-insulating β-Ga_2O_3 substrates with a UID thickness >400 nm, were ion implanted with Si to a total dose of 7×10^{14} cm^{-2} at three energies (15-115 keV) through an SiO_2 cap (20 nm) to yield a 100 nm box profile with a concentration of 5×10^{19} cm^{-3}. Secondary ion mass spectrometry (SIMS) was used to compare implant profiles to SRIM simulated ion ranges, and to quantify Si diffusion during annealing. A wide range of annealing conditions were studied using a load-locked ultrahigh vacuum compatible quartz tube furnace with precise gas control. Anneal times were varied from 10 to 120 minutes, temperatures from 850 to 1000 °C, and the anneal ambient gas was varied by mixing research plus (RP) N_2 with ultra-high purity (UHP) O_2 to control the oxygen partial pressure (pO_2) between $<10^{-6}$ and 1.0 bar. Gases were also selectively passed over a desiccant to reduce the water vapor partial pressure to $<10^{-8}$ bar. Sheet resistance, carrier activation, and mobility were determined using van der Pauw structures. Annealing in extremely low pO_2 (forming gas 4% H_2/N_2) resulted in decomposition of the Ga_2O_3, while annealing at pO_2 above 10^{-2} bar resulted in minimal carrier activation. Within the moderate pO_2 range, minimizing the partial pressure of water vapor was shown to be critical to achieve high carrier activation, with the negative impact of water vapor becoming more significant with increasing

pO_2. Data, however, suggests that a trace level of water vapor may slightly improve carrier activation.Short duration anneals resulted in higher carrier activation with longer times resulting in "over annealing" and reduced carrier density. Optimal anneal temperatures were determined to be between 900 and 950 °C, with lower temperatures showing reduced mobility and higher temperatures exhibiting reduced carrier activation and increased Si diffusion. The optimized anneal conditions for this implant were found to be at 950 °C for 20 minutes under dried RP N_2, with an extended gas purge of the furnace prior to the anneal to remove any residual water vapor, resulting in 88% carrier activation and a mobility of 72 cm^2/V-s (R_s = 130 Ω/sq).

Electronic Transport and Breakdown Phenomena
Room Jefferson 1 & Atrium - Session ET-MoP

Electronic Transport and Breakdown Phenomena Poster Session

ET-MoP-2 Electric Field Mapping in β-Ga_2O_3 by Photocurrent Spectroscopy, ***Darpan Verma**, M. Adnan, S. Dhara,* Ohio State University*; C. Sturm,* Universitat Leipzig, Germany*; S. Rajan, R. Myers,* Ohio State University

Power electronics devices suffer from unexpected field non-uniformity, and high field often degrades these devices by limiting their lifetime. Electric-field mapping could aid in the design of device features non-destructively by identifying breakdown regions. We will discuss progress in developing an E-field mapping technique that can spatially map out the E-field maxima in β-Ga_2O_3 space charge regions and could identify E-field hotspots at which the breakdown is likely. Previously, we showed that the Exciton Franz-Keldysh (XFK) effect can be used to estimate the local E-field maximum in (010) β-Ga_2O_3 Schottky diodes based on the redshift of the photocurrent spectral peak.[1] In that study, we implemented an XFK model using an analytical approximation for the XFK effect based on the modified Wannier-Mott model. Here, we extend these measurements to higher photon energies (< 5.6 eV) in (001) β-Ga_2O_3 Schottky diodes, and observe a total of three absorption peaks whose intensity varies with the angle of the linear polarization of the monochromatic UV light incident on the device. The three peaks at 4.9 eV, 5.2 eV and at 5.5 eV, match quasi-particle-DFT transitions as well as measurements in β-Ga_2O_3 from previous studies[2,3]. Peaks at 4.9 eV and 5.2 eV correspond to excitons polarized within the a-c plane, and the peak at 5.5 eV corresponds to exciton along the b axes. These peaks red shift with bias and can be calibrated to serve as an E-field sensors. A well-calibrated vertical Schottky barrier diode was fabricated on a 10um thick HVPE grown (001) β-Ga_2O_3 epitaxial layer (N_D=1.5E16/cm^3). For the top Schottky contact, a circular Pt (5nm) layer was deposited by E-beam evaporation. Further, leaving the center of the Pt layer exposed for light illumination, a circular ring (overlapping the thin Pt layer) with a contact pad was fabricated using Pt/Au (30/70nm). Afterward, an ohmic back contact of Ti/Au (30/70nm) was blanket deposited. At this structure, the parallel-plate electric field can be theoretically estimated to calibrate the redshift of the photocurrent peaks to E-field values and convert the spatially-resolved photocurrent spectra into mapped E-field values across the whole device active region.

References:

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ET-MoP-3 Activation of Si, Ge, and Sn Donors in High-Resistivity Halide Vapor Phase Epitaxial β-Ga_2O_3:N, ***Joseph Spencer**,* Naval Research Laboratory/ Virginia Tech CPES*; M. Tadjer, A. Jacobs, M. Mastro, J. Gallagher, J. Freitas, Jr,* Naval Research Laboratory*; T. Tu, A. Kuramata, K. Sasaki,* Novel Crystal, Japan*; Y. Zhang,* Virginia Tech (CPES)*; T. Anderson, K. Hobart,* Naval Research Laboratory

With an ultra-wide bandgap (4.8eV), high critical field (6-8MV/cm) and melt-growth capability, the popularity of Gallium oxide (GO) has surged within the material growth and electronic device fields. Even with an UWBG, dopants such as Si and Sn have been shown to be shallow donors (30 and 60meV, respectively) [1-2]. It has also been demonstrated that the addition of nitrogen acceptors allows for the UID level to fall as low as $10^{14}cm^{-3}$, extending the doping range of GO by over an order of magnitude [3,4]. The inclusion of N also results in a highly resistive current blocking layer (CBL) in GO due to the deep acceptor state formed by the N dopants. In this work we demonstrate how implanted donors can overcompensate the highly resistive GO:N CBL, resulting in highly conductive films while the unimplanted regions remain highly resistive.

Halide vapor phase epitaxial (HVPE) films were grown on semi-insulating (001) GO:Fe substrates. Prior works [5] characterized the films using Secondary ion mass spectroscopy (SIMS) to confirm the presence of the N acceptor and 9.2 µm thickness. C-V measurements showed a net free carrier concentration below the detectable limit of 10^{14} cm^{-3} (N_D-N_A). Lateral Schottky diodes showed breakdown voltages that surpassed 2kV for the resistive films [5].

Linear/circular transfer length method (LTLM/CTLM) and van der Pauw (VdP) structures were patterned for donor implantation. Si, Ge, and Sn donors were implanted with a box profile of 100nm at a dose of $3.3^{14}cm^{-2}$. Implanted donors were activated with a rapid thermal anneal (RTA) at 925C for 30min in N2. The LTLM/CTLM and VdP structures were isolated using an 800W BCl_3 reactive ion etcher for a 150nm etch. Ti/Au ohmic contacts were deposited followed by a contact anneal.

A contact resistance (R_c) of 1.2 Ωmm and 2.3 Ωmm for the Si and Sn implanted samples, respectively was measured from LTLM/CTLMs. Temperature dependent Hall effect measurements (15-300K) gave the sheet carrier concentration (n_s), sheet resistance (R_{sh}), and mobility (µ). Hall structures that did not receive implantation of the active region between the ohmic contacts could not be measured due to excessive resistance demonstrating retention of N doped film resistivity. Full implanted VdP structures were highly conductive and measurable. At 300K, the Si, Ge, and Sn doped samples achieved mobilities, sheet resistances, and sheet electron densities of 86, 71, and 59 cm2/Vs, 324, 941, and 1750 Ω/sq, and 2.25e14, 9.3e13, and 6.0e13 cm^{-2} respectively. The implant activation efficiency was found to be 66%, 28%, and 18% for Si, Ge, and Sn, respectively. See supplemental page for references.

Heterogeneous Material Integration
Room Jefferson 1 & Atrium - Session HM-MoP

Heterogeneous Material Integration Poster Session

HM-MoP-1 Structural and Thermal Transport Analysis of Wafer Bonded β-Ga_2O_3 |4H-SiC, ***Michael Liao**, K. Huynh, Y. Wang,* UCLA*; Z. Cheng,* UIUC*; J. Shi,* GaTech*; F. Mu,* IMECAS, China*; T. You, W. Xu, X. Ou,* ShanghaiTech, China*; T. Suga,* Meisei University, Japan*; S. Graham,* GaTech*; M. Goorsky,* UCLA

The impact of post-bond annealing on the structural and thermal characteristics of 140-nm thick exfoliated ($\underline{2}01$) β-Ga_2O_3 (via H^+ ion implantation [1]) direct wafer bonded to (0001) 4H-SiC was studied. For these studies, 30 nm amorphous alumina was grown on the β-Ga_2O_3 substrates prior to bonding as an interlayer between the β-Ga_2O_3 and 4H-SiC. The surface activated bonding technique was utilized for bonding, which induces a thin ~nm amorphous interfacial region at the bonded interface (alumina | 4H-SiC) [2]. We demonstrate annealing the bonded structure at 800 °C in ambient air up to 1 hour is beneficial: (1) removal of residual strain in the exfoliated β-Ga_2O_3 layer that was due to the exfoliation implant, (2) reduction of lattice mosaicity in the β-Ga_2O_3 layer, and (3) recrystallization of the amorphous bonded interfacial region. The thermal characteristics correspondingly improve with the improvement in structural characteristics. The thermal conductivity of the as-bonded β-Ga_2O_3 layer was 2.9 W/m·K and the thermal boundary conductance (TBC) of the bonded interface was 66 MW/m^2·K [2]. After annealing at 800 °C for 1 hour, triple-axis X-ray diffraction ω:2θ measurements showed a reduction in strain for the β-Ga_2O_3 layer and the symmetric ($\underline{2}01$) rocking curve widths. Transmission electron microscopy images of the bonded interface show that the amorphous bonded interfacial region recrystallized. We simultaneously observe a doubling of the β-Ga_2O_3 thermal conductivity to 6.0 W/m·K and a twenty percent increase in the TBC. While the previous results showed the promise of exfoliation of b-Ga_2O_3 on 4H-SiC, here we demonstrate that annealing further improves both structural and thermal properties.

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The authors M.E.L., K.H., Y.W., Z.C., J.S., S.G., and M.S.G. would like to acknowledge the support from the Office of Naval Research through a MURI program, grant No. N00014-18-1-2429.

HM-MoP-2 Advances in Plasma-Enhanced Atomic Layer Deposited (PEALD) Ga_2O_3 Films, ***Virginia Wheeler***, *A. Lang, N. Nepal, E. Jin, D. Katzer, V. Gokhale, B. Downey, D. Meyer,* US Naval Research Laboratory

Ga_2O_3 is a promising material for next generation electronics. Recently, we demonstrated that plasma-enhanced atomic layer deposition (PEALD) can be used to attain heteroepitaxial metastable phases [1], specifically α and ε/κ, and the full stoichiometric range of $(Al_xGa_{1-x})_2O_3$ films. PEALD is a conformal, energy-enhanced synthesis method for thin films with many advantages, including: deposition at reduced growth temperatures, access to metastable phases, elimination of miscibility gaps, and improved crystallinity and growth rates over conventional ALD. In this work, we present new insights into the microstructure and uniformity of metastable ε-Ga_2O_3 films integrated on GaN. Additionally, we explore the use of PEALD for fabricating metastable nucleation layers that can be expanded by more traditional, faster deposition techniques.

Transmission electron microscopy (TEM) was used to correlate PEALD parameters with the resulting Ga_2O_3 microstructure on GaN substrates. A low temperature, low pressure PEALD regime produced ~95% epsilon phase films with a strained interfacial layer and 10-50nm grains. The remaining portion was a combination of alpha and beta phases that were primarily segregated towards the surface of the film. In comparison, a higher temperature, high-pressure growth regime produced uniform, pure epsilon phase films with 2-5 nm grains. The abrupt interface was fully relaxed with misfit dislocations at a spacing of ~2nm, explaining the resulting ε-Ga_2O_3grain size. There was no evidence of kappa or gamma phase as often seen with low temperature heterogeneous integration of Ga_2O_3 films.

While PEALD is beneficial for depositing thin films of metastable phases, practical devices often require much thicker barrier and active layers. For this reason, we investigated integrating PEALD metastable Ga_2O_3 films with traditional semiconductor growth techniques, such as molecular beam epitaxy (MBE), capable of extending these layers beyond 100 nm in thickness. The same MBE conditions were used to deposit Ga_2O_3 films on GaN substrates with and without PEALD ε-Ga_2O_3 nucleation layers.Those deposited without the PEALD nucleation layer produced β-phase films, while those with nucleation layers resulted in pure ε-phase films. We also show a similar capability using metal-organic chemical vapor deposition (MOCVD).This shows importance of PEALD for realizing practical device structures using metastable phases.This concept could also be expanded to α-Ga_2O_3 film, though this is more easily achieved directly on sapphire substrates.

[1] Wheeler et al., *Chem. Mater.* 2020, 32, 1140-1152

HM-MoP-3 Grafted Si/Ga2O3 pn Diodes, *H. Jang, D. Kim,* University of Wisconsin - Madison; *J. Gong,* University of Wisconsin at Madison; *F. Alema, A. Osinsky,* Agnitron Technology Inc.; *K. Chabak,* Air Force Research Laboratory; *G. Jessen,* BAE Systems; *G. Vincent,* Northrup Grumann; *S. Pasayat, C. Gupta,* University of Wisconsin - Madison; ***Zhenqiang Ma***, 1415 Engineering Drive

Gallium oxide (Ga_2O_3) is a promising semiconductor for the next-generation power devices, due to its ultra-wide bandgap (4.9 eV), high electron saturation velocity (1.1×10^7 cm/s), and high breakdown electric field (8 MV/cm) and the mature growth technique for large diameter native substrates. While many high-performance unipolar devices, e.g., field-effect transistors (FET) and Schottky diodes, have been reported recently, the lack of p-type Ga_2O_3 limits the development of Ga_2O_3 based bipolar devices. Wafer bonding of p-type diamond with Ga_2O_3 and growth of p-type polycrystalline on Ga_2O_3 have been attempted to realize bipolar (pn) devices with limited performance. The recent semiconductor grafting approach shows the potential of forming semiconductor heterostructures without concerning about lattice mismatch. The grafting approach could be exploited to form p-n heterojunctions by combining n-type Ga_2O_3 with monocrystalline p-type semiconductors. In this talk, preliminary results of p-Si/n-Ga_2O_3 pn diode fabricated by semiconductor grafting will be presented. The Ga_2O_3 epi layer consists of Sn-doped 150 nm n- (2e17 cm^{-3}) on a Sn doped 500-600µm n^+-Ga_2O_3 (5e18 cm^{-3}) substrate. A ~185 nm thick boron doped (5e19 cm^{-3}) single crystalline Si (native oxide free) was released from SOI and transferred to the top of the n-Ga_2O_3 epi substrate. A thermal anneal of 350 °C for 5 mins was performed to form chemical bonding while the top layer of Ga_2O_3 is expected to serve as the interface passivation layer. Ni/Au/Cu/Au metal stack was deposited on the p-Si as anode contact and a Ti/Au/Cu/Au was deposited on the backside (n+) Ga_2O_3 as cathode contact. Without any further thermal annealing, we have achieved an I-V characteristic with I_{on}/I_{off} = 1.5e8 at ±2 V and ideality factor n = 1.4. The device performances were compared with a Schottky diodes fabricated using the same epi substrate. The study has shown the feasibility of grafting in developing Ga_2O_3-based bipolar devices, despite that further improvement of device performance is expected.

Advanced Characterization Techniques
Room Jefferson 2-3 - Session AC-TuM

Advanced Characterization & Microscopy

Moderator: Ginger Wheeler, Naval Research Laboratory

10:45am **AC-TuM-10 Defects in Gallium Oxide – How We "See" and Understand Them**, ***Jinwoo Hwang***, The Ohio State University **INVITED**

Due to the low crystal symmetry, gallium oxide can display formation of unique defects ranging from point defects to phase transition that are important to understand, as such defects directly correlate to the properties of the material and performance of gallium oxide-based devices. This presentation will overview the recent progress in the atomic scale characterization of various defects in gallium oxide and aluminum gallium oxide using scanning transmission electron microscopy. We make a direct connection between the atomic structure of these defects and important properties of gallium oxide materials and devices, including growth characteristics of the films as well as their electric and thermal properties. The topics will include: (i) formation of point defects and complexes, (ii) alloy incorporation and phase stability in aluminum gallium oxide, (iii) formation of 2D defects, such as stacking faults and twins, (iv) phase transformation induced by incorporation (or diffusion) of impurity atoms, (v) defects at interfaces with metal contacts and their influence on thermal interface resistance, and (vi) defects created by ion implantation of gallium oxides. The new information that we summarize in this presentation is expected to help achieve atomic scale control of defects in gallium oxide materials and devices for the next generation power electronics applications.

11:15am **AC-TuM-12 Atomic-Scale Investigation of Point and Extended Defects in Ion Implanted β-Ga_2O_3**, ***Hsien-Lien Huang***, *C. Chae,* The Ohio State University; *A. Senckowski, M. Wong,* Penn State University; *J. Hwang,* The Ohio State University

Atomic scale scanning transmission electron microscopy (STEM) was used to study the formation of point and extended defects, as well as phase transformations in Si-implanted β-Ga_2O_3. Quantitative analysis of the atomic column intensities in STEM images acquired with an absolute scale, when combined with precise electron scattering simulations, can directly visualize the detailed structure of atomic and nanoscale defects in materials. For example, our previous studies have revealed the formation of different types of point and extended defects, including the interstitial-divacancy complexes in β-Ga_2O_3 and planar defects and phase transition in $(Al_xGa_{1-x})_2O_3$ that directly correlate with Al incorporation into the lattice. In the present study, we performed a correlative study on the structural change and defect formation in Si implanted β-Ga_2O_3 (edge-defined, film-fed (EFG)-grown (001) β-Ga_2O_3 substrate) as a function of Si dose, using a combination of STEM and secondary ion mass spectrometry (SIMS). Peak Si concentrations of 10^{18}-10^{21} cm^{-3} were investigated. Different types of point defects and their complexes were observed in lower Si concentrations (< ~ 10^{19} cm^{-3}), which include cation interstitials and substitutional atoms into the oxygen positions. The types and concentrations of those defects change as a function of the depth of the implantation. The implication of the observed defects to electronic properties will be discussed. High concentration of point defects at a local region also led to the formation of a unique type of extended defect, which apparently involves a large strain field that extends up to a few tens of nanometers. At higher Si concentrations (> 10^{20} cm^{-3}), the structure tends to transform into different Ga_2O_3 phases, including γ-Ga_2O_3 which, according to our previous investigation, has a close relationship to the extended defects in β-Ga_2O_3. In situ annealing of the samples was performed to understand the structural evolution and diffusion dynamics of the implanted materials. The precise atomic scale information on defect formation and their evolution provides an important guidance to understand and control the ion implantation of Ga_2O_3 materials and devices which is crucial to advance them to next generation ultrawide-bandgap applications.

11:30am **AC-TuM-13 Microscopic and Spectroscopic Analysis of (100), (-201) and (010) $(Al_xGa_{1-x})_2O_3$ Films Using Atom Probe Tomography**, *J. Sarker,* University at Buffalo-SUNY; *A. Bhuiyan, Z. Feng, L. Meng, H. Zhao,* The Ohio State University; ***Baishakhi Mazumder,*** University at Buffalo-SUNY

$(Al_xGa_{1-x})_2O_3$ is an emerging ultra-wide bandgap semiconductor with a bandgap tunability of 4.8 - 8.7 eV and highly promising for high power electronics [1]. The Al inclusion limit in $(Al_xGa_{1-x})_2O_3$ varies with growth orientation. While (010)–$(Al_xGa_{1-x})_2O_3$ is single β–phase stable till 27% Al, (-201) and (100)–$(Al_xGa_{1-x})_2O_3$ exhibit β–phase for >50% Al [2]. The Al incorporation in $(Al_xGa_{1-x})_2O_3$ for different orientations are limited by phase segregations, chemical heterogeneity and domain rotations due to difference in surface free energy. The higher the surface free energy, the lower the Al incorporation at the growth surface. Also, as the surface free energy varies for different growth orientation, the binding energies would be different which play a significant role in Al inclusion range in (100), (-201) and (010)–$(Al_xGa_{1-x})_2O_3$ films. Therefore, a comprehensive understanding of the film's structural-chemical morphology and properties (surface energy, binding energy and bond lengths) of (100), (-201) and (010)–$(Al_xGa_{1-x})_2O_3$ is needed to achieve films with high Al% for high power transistors.

Here, we employed atom probe tomography (APT), a nanoanalytical tool combining microscopy to provide chemical imaging and spectroscopy to reveal qualitative binding energy/bond length information of material. The nanoscale structure-chemistry of (100), (-201) and (010)–$(Al_xGa_{1-x})_2O_3$ varying Al composition was probed. From the in-plane lateral Al/O distribution, $(Al_xGa_{1-x})_2O_3$ layers with 20% Al are found to be homogeneous in (100), (-201) and (010) orientation while $(Al_xGa_{1-x})_2O_3$ layers with 50% Al are relatively less homogeneous in each case. This is attributed to the higher surface migration length of Al atoms compared to that of Ga atoms. The APT spectroscopy was used to determine the relative bond length information of Ga–O and Al–O for (100), (-201) and (010)–$(Al_xGa_{1-x})_2O_3$ films varying Al content. The observed APT spectroscopy result reveals that the bond length of Ga–O and Al–O changes as the $(Al_xGa_{1-x})_2O_3$ growth orientation varies.

This work will provide critical understanding and insights on the structural chemistry and bond lengths of $(Al_xGa_{1-x})_2O_3$ films with different growth orientations and will aid in optimizing the growth towards developing $(Al_xGa_{1-x})_2O_3$ films with high Al%.

Acknowledgment: NSF (Grant No. 2114595; 1810041 and 2019753) and AFOSR (FA9550-18-1-0479)

Reference: 1. Bhuiyan et al. APL Materials, **8**, 031104 (2020); 2. Bhuiyan et al. Appl. Phys. Lett. **117**, 142107 (2020)

11:45am **AC-TuM-14 Phase and Microstructure Evolution of κ-Ga_2O_3 Thin Films Grown by MOCVD**, ***Jingyu Tang***, *K. Jiang,* Carnegie Mellon University, China; *M. Cabral, A. Park,* Carnegie Mellon University; *L. Gu,* Carnegie Mellon University, China; *R. Davis , L. Porter,* Carnegie Mellon University

Ga_2O_3 is an ultra-wide bandgap semiconductor that has larger values of bandgap, Baliga's figure of merit, and breakdown electric field than SiC and GaN. There are four commonly accepted polymorphs of Ga_2O_3, namely trigonal α (corundum structure), monoclinic β, orthorhombic κ, and cubic γ (cation deficient spinel structure) phases. Of those four polymorphs, β-Ga_2O_3 has been the most investigated, as this phase is the thermodynamically stable phase from room temperature to the melting point at atmospheric pressure[1-2]. However, the lower symmetry of β-Ga_2O_3 results in anisotropic optical and electronic properties. Compared with β-Ga_2O_3, κ-Ga_2O_3 has higher symmetry and some unique properties. κ-Ga_2O_3 shows spontaneous polarization (Psp) parallel to the c-axis and thus a high-density two-dimensional electron gas can be formed at the interface without doping. The reported values of Psp are 0.23 C/m^2 [3] and 0.242 C/m^2 [4], respectively, which are about an order of magnitude higher than those of GaN and AlN. In this study, nominally phase pure κ-Ga_2O_3 films were successfully grown on vicinal c-plane sapphire (0.15° offcut toward m-plane) by low-pressure metal-organic chemical vapor deposition[5]. Phase and microstructural characterizations were conducted using a complementary suite of tools. High-angle annular dark-field scanning transmission electron microscopy of a κ-Ga_2O_3 film grown under optimum conditions revealed the pseudomorphic growth of 3-4 monolayers of α-Ga_2O_3 at the interface, followed by a 20-60 nm transition layer containing a mixture of β- and γ-Ga_2O_3 which was covered by an ~700 nm-thick layer of phase-pure κ-Ga_2O_3. The occurrence of these phases and their sequence of formation will be presented. X-ray diffraction (XRD) and scanning electron microscopy investigations showed that the top layer varied between ~100% κ-Ga_2O_3 and ~100% β-Ga_2O_3, depending on the growth temperature and the growth rate. XRD ϕ scans showed in-plane epitaxial relationships and the presence of the three rotational domains in the κ-Ga_2O_3. Atomic force microscopy investigations revealed a smooth surface morphology with a root-mean-square roughness of ~3.5nm for optimum growth conditions. In summary, growth conditions have been established that yield 700 nm-thick films, above a thin transition layer, comprising phase-pure κ-Ga_2O_3; whereas the β-phase is favored at higher growth temperatures and lower growth rates.

12:00pm **AC-TuM-15 Investigation of Extended Defects in Ga2O3 Substrates and Epitaxial Layers using X-ray Topography*, Nadeemullah A. Mahadik,*** *M. Tadjer, T. Anderson, K. Hobart,* Naval Research Laboratory, USA*; K. Sasaki, A. Kuramata,* Novel Crystal Technology, Japan

Recently, beta-gallium oxide (β-Ga_2O_3) has attracted attention for high power devices due to its high bandgap of 4.9eV and possibility of manufacturing large diameter wafers using quasi-equilibrium melt-based techniques, which can have low defects. Extended defects such as dislocations, stacking faults, inclusions, dislocation slip bands etc have proven to have detrimental effects on power and RF device performance and reliability. Defect identification and their mitigation is necessary to fabricate devices that can reach the predicted breakdown and on-state resistance performance for Ga_2O_3 devices. Investigation of extended defects over large diameter Ga_2O_3 wafers, including defect delineation and micro-structural properties can be obtained using high resolution x-ray topography (XRT). In this study, various extended defects were investigated in 100 mm diameter Ga_2O_3 wafers with 10µm thick epitaxial layers using multiple reflection XRT characterization to identify defect types and distinguish defects in both substrates and epitaxial layer.

For this study, a 100 mm diameter, edge-defined, film-fed (EFG) growth Ga_2O_3 wafer with 10 mm epitaxial layer grown via halide vapor phase epitaxy (HVPE) was obtained from Novel Crystal Technology. XRT imaging was performed on a Rigaku XRTMicron system equipped with a 1.2kW Cu/Mo dual rotating anode, high precision X, Y, f goniometer and 5.4mm/2.2mm pixel dual X-ray cameras. Imaging was performed using Mo ka_1 in transmission geometry with g=(020) and in reflection geometry with g=(-809), (607), and (-44,10). Imaging using Cu ka1 was also performed in reflection geometry with g=(224) and (514). Using these various imaging conditions the penetration depth of the X-rays was controlled in the sample. Hence, identification and delineation of a variety of extended defects from both the epitaxial layers as well as the substrates was performed.

A distribution of basal plane dislocations (BPD) was observed across the wafer with a density ~$3x10^3$ cm^{-2}. These BPDs are primarily within the substrate. Few of the BPDs were observed to propagate into the epitaxial layers. Slip bands were observed emanating from the edge of the wafer in several regions and are within the epitaxial layers only. These are likely due to residual damage in the wafer edge processing. Additionally pits were identified within the epitaxial layer, which could be due to pitting occurring by Ga droplets during the HVPE process. Other defects such as inclusions, surface dislocations, and scratches were also observed. Detailed micro-structure and dislocation analysis will be presented on the extended defects observed in the multiple XRT images.

Plenary Session
Room Jefferson 2-3 - Session PS1-TuM

Plenary Session I
Moderator: Dr. Kelson Chabak, Air Force Research Laboratory

8:45am **PS1-TuM-2 Plenary Lecture: Gallium Oxide Electronics - Device Engineering Toward Ultimate Material Limits*, Siddharth Rajan,*** The Ohio State University **INVITED**

The unique material properties of Gallium Oxide make it promising for a range of future applications, but innovative materials and device engineering are needed to translate these ultimate material limits to real technology. This presentation will discuss our recent work on epitaxy, heterostructure design, and electrostatics to achieve high-performance $\beta\beta$-Ga2O3 lateral and vertical electronic devices.

Recent work on lateral Gallium Oxide transistors have demonstrated excellent electron transport and device characteristics. We will discuss some advances in materials growth and device design for lateral structures which enabled key transistor demonstrations including the first $\beta\beta$-(Al,Ga)2O3/$\beta\beta$-Ga2O3 modulation-doped structures with excellent transport properties, double-heterostructure modulation-doped structures, scaled delta-doped transistors with cutoff frequency of 27 GHz, and self-aligned lateral field effect transistors with > 900 mA/mm current density.

Significant potential exists for Gallium Oxide devices with 3-dimensional geometries for enhanced field and thermal engineering. We will outline the use of a new damage-free epitaxial etching technique using Ga atomic flux that enables highly precise fabrication of 3-dimensional structures. We will also show some applications of atomic Ga-flux etching to realize excellent field termination in vertical diodes, and lateral FINFETs with enhanced performance.

The high breakdown field of Gallium Oxide makes it critical to manage electric field profiles within the device. Extreme-permittivity dielectrics provide unique opportunities to create devices that can sustain extreme fields without premature breakdown of metal-semiconductor and dielectric-semiconductor interfaces. We will discuss promising results related to this approach, such as BaTiO3/Ga2O3 heterojunctions that enable more than 5.7 MV/cm vertical breakdown field and BaTiO3/Ga2O3 transistors with > 5.5 MV/cm breakdown field, the highest for a field effect transistor in any material system, and with state-of-art power switching figure of merit of 586 MW/cm2.

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Theory, Modeling and Simulation
Room Jefferson 2-3 - Session TM-TuM

Characterization & Modelling III
Moderator: Michael Scarpulla, University of Utah

9:15am **TM-TuM-4 First-Principles Modeling of Ga_2O_3*, Hartwin Peelaers,*** University of Kansas **INVITED**

β-Ga_2O_3 is a wide-band-gap semiconductor with promising applications in high-power electronics and photodetectors that are transparent to visible light. In this talk, I will show how first-principles calculations, based on density functional theory with hybrid functionals, can be used to predict and explain the properties of Ga_2O_3.

We first focus on modifying Ga_2O_3's properties for electronic applications through doping. While n-type doping is straightforward, p-type doping is elusive, with only deep acceptors available. We explore the properties of possible acceptors, and discuss the viability of obtaining semi-insulating material [1]. All dopants we considered lead to deep acceptor levels that are more than 1.3 eV above the valence-band maximum. N and Mg were identified as the most promising deep acceptors. We evaluated incorporation in different configurations, and considered the effect of native defects as well as complexes. We also predict diffusion activation energies, finding that Mg is significantly more mobile.

Alloying allows to modify the lattice constants, band gaps, and conduction-band offsets. We will provide quantitative results for alloys with In_2O_3 and Al_2O_3 [2,3].

When Ga_2O_3 is used as a transparent conducting oxides (TCO), two conflicting properties have to be balanced: transparency and conductivity. The requirement of transparency is typically tied to the band gap of the material being sufficiently large to prevent absorption of visible photons. This is a necessary but not sufficient condition: indeed, the high concentration of free carriers, required for conductivity, can also lead to optical absorption. This absorption can occur through direct absorption to higher-lying conduction band states, or by an indirect process, for example mediated by phonons or charged impurities. We will elucidate the fundamental limitations of optical absorption in Ga_2O_3 and shed light on experimental observations [4,5].

Work in collaboration with J.L. Lyons, S. Seacat, C.G. Van de Walle, and J.B. Varley.

[1] H. Peelaers, J. L. Lyons, J. B. Varley, and C. G. Van de Walle, APL Mater. **7**, 022519 (2019).

[2] H. Peelaers, D. Steiauf, J. B. Varley, A. Janotti, and C. G. Van de Walle, Phys. Rev. B **92**, 085206 (2015).

[3] H. Peelaers, J. B. Varley, J. S. Speck, and C. G. Van de Walle, Appl. Phys. Lett. **112**, 242101 (2018).

[4] H. Peelaers and C.G. Van de Walle, Appl. Phys. Lett. **111**, 182104 (2017).

[5] H. Peelaers and C.G. Van de Walle, Phys. Rev. B **100**, 081202(R)(2019).

9:45am **TM-TuM-6 Theory of Acceptor-Donor Complexes in Ga_2O_3**, *I. Chatratin, F. Sabino,* University of Delaware; *P. Reunchan,* Kasetsart University, Thailand; ***Anderson Janotti,*** University of Delaware

Ga_2O_3 has attracted great attention as a promising material for high-power electronic devices due to a very large band gap and high breakdown voltage. It can be easily doped *n*-type, with Si, Ge, or Sn as shallow donors, but difficult to dope *p*-type. All tested candidate acceptor impurities lead to deep acceptor levels, lying at ~1 eV above the valence band. These deep acceptors are quite useful for making semi-insulating Ga_2O_3 layers, which are important components in many device designs. The interactions between acceptors, such as nitrogen or zinc, and donor impurities may play important role in the performance of the Ga_2O_3 semi-insulating layers. Using electronic structure calculations based on hybrid density functional theory, we investigate the interactions between acceptor and donor impurities in different possible configurations of acceptor-donor complexes considering all the inequivalent cation and anion sites of the β-Ga_2O_3 crystal structure. We calculate binding energies of the complexes and discuss changes in transition levels compared to those of the isolated species. These results aim at facilitating the experimental characterization of acceptor impurities to further the development of Ga_2O_3-based electronic devices.

10:00am **TM-TuM-7 Donor Doping of Monoclinic and Corundum $(Al_xGa_{1-x})_2O_3$**, ***Darshana Wickramaratne,*** US Naval Research Laboratory; *J. Varley,* Lawrence Livermore National Laboratory; *J. Lyons,* US Naval Research Laboratory

Designs of electronic devices using $(Al_xGa_{1-x})_2O_3$ (ALGO) as the barrier layer and gallium oxide (Ga_2O_3) as the active layer are being considered. The success of these devices is predicated in part on the ability to achieve controlled doping of the ALGO barrier layer. This requires shallow centers across the alloy composition range to be identified. The fact that Ga_2O_3 is most stable in the monoclinic structure, which is different from the ground-state corundum structure of Al_2O_3 also needs to be accounted for.

Using first-principles calculations based on a hybrid functional we investigate the prospects for *n*-type doping monoclinic and corundum ALGO alloys across the entire alloy composition range. We explore the properties of group-IV (C, Si, Ge, and Sn) and transition metal (Hf, Zr, and Ta) substitutional dopants. In Ga_2O_3, all of these dopants are shallow donors. However, in Al_2O_3 they are all deep defects, characterized by the emergence of deep levels within the band gap. Combining our calculations of dopant charge-state transition levels together with information about the ALGO alloy band offsets for both polymorphs, we estimate the critical Al composition at which each dopant transitions from being a shallow to a deep donor. We identify Si to be the most efficient dopant to achieve *n*-type conductivity in high Al-content corundum and monoclinic ALGO [1].

This work was supported by the ONR/NRL 6.1 Basic Research Program.

[1] J. B. Varley, A. Perron, V. Lordi, D. Wickramaratne, and J. L. Lyons, *Appl. Phys. Lett.* **116**, 172104 (2020).

10:15am **TM-TuM-8 The Co-Design, Fabrication, and Characterization of a Ga2O3-on-SiC MOSFET**, ***Yiwen Song,*** Pennsylvania State University; *A. Bhattacharyya,* University of Utah; *A. Karim, D. Shoemaker,* Pennsylvania State University; *H. Huang,* Ohio State University; *C. McGray,* Modern Microsystems, Inc.; *J. Leach,* Kyma Technologies, Inc.; *J. Hwang,* Ohio State University; *S. Krishnamoorthy,* University of California at Santa Barbara; *S. Choi,* Pennsylvania State University

β-phase gallium oxide (Ga_2O_3) is an emerging ultrawide bandgap semiconductor (E_G ~ 4.8 eV) that offers potential for significant improvement in the performance and manufacturing cost of today's commercial wide bandgap semiconductor devices. However, due to the poor thermal conductivity of the Ga_2O_3 (10.9-27 W/mK), overheating has become a major bottleneck to the commercialization of Ga_2O_3 devices.

In response to this critical problem, a Ga_2O_3/4H-SiC composite wafer was fabricated. Thermo-physical properties of the composite wafer were characterized using a combination of laser-based pump-probe methods. Scanning transmission electron microscopy and modeling suggest that the interfacial thermal boundary resistance (TBR) is mainly limited by the low thermal conductivity of the interlayer used for the fusion bonding process. A n-type Ga_2O_3 channel layer was successfully grown on the composite wafer using low-temperature metalorganic vapor phase epitaxy (MOVPE). Metal-oxide-semiconductor field effect transistors (MOSFETs) were subsequently fabricated on the composite substrate. In situ nanoparticle-assisted Raman thermometry was used to compare the self-heating behavior of MOSFETs fabricated on a Ga_2O_3 substrate and the Ga_2O_3/4H-SiC composite wafer. Under steady-state operation, a 56% reduction in channel temperature was achieved in the devices fabricated on the composite wafer as compared to the homoepitaxial devices on the Ga_2O_3 native substrate. However, the improvement in the device thermal resistance is limited under high frequency switching operation due to the low thermal diffusivity of the Ga_2O_3 layer, highlighting the importance of minimizing the Ga_2O_3 layer thickness. Transient electro-thermal device modeling was performed to assess the cooling effectiveness of optimized composite substrates for the case of both single- and multi-finger devices. Simulation results suggest that additional top-side cooling using a high thermal conductivity passivation overlayer such as polycrystalline diamond allows to achieve high heat transfer performance under high frequency operating conditions.

This comprehensive study on both material- and device-levels provides key insight into the effective thermal management of $Ga_{-2}O_3$ device technologies.

Dielectric Interfaces
Room Jefferson 2-3 - Session DI-TuA
Processes & Devices II

Moderator: Hongping Zhao, Ohio State University

3:45pm **DI-TuA-9 Dielectric Integration on (010) β-Ga_2O_3: Al_2O_3, SiO_2 Interfaces and their Thermal Stability***, **Ahmad Islam**,* Air Force Research Laboratory*; A. Miesle,* University of Dayton*; M. Dietz,* Wright State University*; K. Leedy, S. Ganguli,* Air Force Research Laboratory*; G. Subramanyam,* University of Dayton*; W. Wang,* Wright State University*; N. Sepelak, D. Dryden,* KBR, Inc.*; T. Asel, A. Neal, S. Mou, S. Tetlak, K. Liddy, A. Green, K. Chabak,* Air Force Research Laboratory

Metal-oxide-semiconductor (MOS) devices made using the newest compound semiconductor β-Ga_2O_3 generally do not exhibit high quality, electronic-grade dielectric integration. These are mainly due to the deposition of dielectrics on low-quality substrates. The device fabrication processes also introduce additional defects within the device. The fabricated devices therefore have > 10^{12} cm^{-2} defect density and show a large hysteresis during the C-V and I-V characterization and a large AC-DC dispersion during pulse characterization. A reduction of hysteresis and dispersion often uses a high temperature process that compromises the gate leakage and the breakdown strength of the dielectric. Dielectrics in β-Ga_2O_3 devices also loses its integrity when devices are subjected to high temperature, extreme environment applications.

Here, we will highlight the general challenge for integrating dielectrics on β-Ga_2O_3, address the associated requirements for obtaining high-quality dielectric and dielectric/β-Ga_2O_3 interface, and present our recent works on the integration of $Al_2O_3$and SiO_2 dielectrics on (010) β-Ga_2O_3 [1]. We will show how surface roughness can play key role in controlling interface defect density in β-Ga_2O_3 MOS capacitors. We will also discuss the role of surface cleanliness (using, for example, piranha treatment), the removal of surface defective layer using HF, and the role of post-deposition annealing in reducing interface defect density [2]. Finally, we will compare the thermal stability of SiO_2 and Al_2O_3deposited on (010) β-Ga_2O_3 substrates [3]. All these considerations will eventually allow electronic-grade integration of dielectrics on β-Ga_2O_3substrates needed to attain high breakdown voltage in power electronics applications and also to attain low AC-DC dispersion and high operating frequency in RF applications.

[1] Islam *et al.*, "Integration challenges for dielectric on β-Ga_2O_3 and their solutions," Proc. of *GOMACTech*, 2022, P31.

[2] Islam *et al.*, "Hysteresis-free MOSCAP made with Al_2O_3/(010)β-Ga_2O_3 interface using a combination of surface cleaning, etching and post-deposition annealing," Proc. of *DRC*, 2021, p. 9467169.

[3] Islam *et al.*, "Thermal stability of ALD-grown SiO_2 and Al_2O_3 on (010) β-Ga_2O_3 substrates," Accepted, *DRC*, 2022.

4:00pm **DI-TuA-10 Deep Etch Field-Terminated β-Ga_2O_3 Schottky Barrier Diodes With 4.2 MV/cm Parallel Plate Field Strength***, **Sushovan Dhara**, N. Kalarickala, A. Dheenan, C. Joishi, S. Rajan,* The Ohio State University

β-Ga_2O_3 Schottky barrier diodes (SBDs) [1-2] are promising devices for next-generation kV-class power switching. In this work, we analyze the effect of BCl_3/Cl_2 based dry etch on [100] and [010] etched vertical sidewalls and demonstrate a deep mesa etch design for efficient edge termination leading to parallel plate fields in excess of 4 MV/cm. We also report on significant depletion of the semiconductor to depths up to several 10's of micron, and remarkable anisotropy in this depletion. The work demonstrated here provides insight into the impact of etching on n-type Ga_2O_3, and shows a promising method to realize efficient field termination for high breakdown field strength SBDs.

Experimental: The SBDs reported here were fabricated on commercially available (001) n-doped β-Ga_2O_3 layers grown by halide vapor phase epitaxy (HVPE). To analyze etch damage in the etched vertical sidewall planes ([010], [100]), rectangular SBD patterns with varying lengths along (100) and (010) directions were designed and etched (~ 4 µm) in ICP-RIE using BCl_3/Cl_2 with the Pt anode metal as the hard mask. Two terminal reverse breakdown showed breakdown voltages of -1150 V (4.23 MV/cm) for the mesa edge terminated devices, whereas the planar devices broke at -530 V (2.87 MV/cm). The removal of material during the etch reduces image charges, and therefore enables very efficient field termination. Analysis of the forward conduction characteristics shows some unusual effects of the plasma exposure creating deep lateral depletion on the order of 10's of microns. Rectangular mesa devices fabricated with the sidewalls as (010) planes were more susceptible to lateral depletion - devices with less than 100 µm spacing between the (010) sidewalls were very resistive. On the other hand, such deep lateral depletion was not seen from the (100) sidewall. We conclude that the plasma exposure of (010) planes leads to the diffusion laterally into the material, creating defects deep inside the material. A possible reason for this could be the diffusion of BCl_3/Cl_2 etch radicals along the (010) direction[3]. This is the first report of the anisotropic and remarkably deep depletion caused by plasma etching in Ga_2O_3. The high parallel plate field (> 4 MV/cm) also suggests that with proper control, deep etching can be a promising way to achieve field termination in Ga_2O_3 SBDs.

We acknowledge funding from DOE / National Nuclear Security Administration under Award Number(s) DE-NA000392, and AFOSR GAME MURI (Award No. FA9550-18-1-0479, project manager Dr. Ali Sayir).

References: [1] W. Li, et al., IEEE EDL,2020. [2] Z. Xia et al., APL,2019. [3] G. Alfieri et al., JAP.,2021.

4:15pm **DI-TuA-11 Demonstration of Low Thermal Resistance in Ga_2O_3 Schottky Diodes by Junction-Side-Cooled Packaging***, **Boyan Wang**, M. Xiao, J. Knoll, Y. Qin,* Virginia Polytechnic Institute and State University*; J. Spencer, M. Tadjer,* U.S. Naval Research Laboratory*; C. Buttay,* Univ Lyon, CNRS, INSA Lyon, Université Claude Bernard Lyon 1, Ecole Centrale de Lyon, Ampère, France*; K. Sasaki,* Novel Crystal Technology, Japan*; G. Lu, C. DiMarino, Y. Zhang,* Virginia Polytechnic Institute and State University

Ga_2O_3 is a promising candidate for power electronics and RF applications, whereas a fundamental limitation of Ga_2O_3 is its low thermal conductivity (k_T). This work studies the impact of the packaging process on Ga_2O_3 device characteristics and measures the junction-to-case thermal resistance ($R_{\theta JC}$) of a 15 A double-side-packaged vertical Ga_2O_3 Schottky barrier diode (SBD) under the bottom-side-cooling and junction-side-cooling schemes.

Fig. 1. shows the schematic and photo of the packaged Ga_2O_3 SBD, device fabrication process [1], and the device structure. 100-nm Ti and 200-nm Ag were deposited on both anode and cathode as the contact layer for silver sintering. Besides serving as an adhesion layer, Ti also functions as a barrier layer to prevent Ag diffusion into Schottky metal in the subsequent sintering process.

Die attach is performed using a pressureless sintering process in air, using a nano-silver paste. The paste is stencil-printed through a 70 µm thick, laser-cut mask. The size of the silver print is increased from 2.5×2.5 mm^2, the size of the mask opening, to about 3×3 mm^2. Once sintered, the assembly is encapsulated in a silicone elastomer for isolation. Fig. 2 summarizes the packaging process.

Fig. 3 shows the forward I-V, reverse C-V and I-V characteristics of the packaged Ga_2O_3 SBD, revealing a turn-on voltage V_{on} of 0.9 V, a forward current of 15 A at 2.15 V, an on/off ratio of 10^{10} extracted at 2 V/0 V, and a breakdown voltage of about 600 V.

Fig. 4 shows the I-V characteristics of the Ga_2O_3 SBD before and after packaging. After packaging, the V_{on} increases, the differential on-resistance reduces, and both forward and reverse leakage current decreases. These shifts are believed to be due to the improvement of the Schottky contact after the 250ºC sintering process.

The $R_{\theta JC}$ measurement is detailed in [2], following the transient dual interface method, i.e., JEDEC 51-14 standard. Fig. 5 shows our $R_{\theta JC}$ measurement set-up, the bottom- and junction-cooling measurements of the same packaged Ga_2O_3 SBD. Fig. 6 shows a much lower $R_{\theta JC}$ (0.5 K/W) under junction-side cooling as compared to the $R_{\theta JC}$ (1.43 K/W) under the bottom-side cooling.

Table I benchmarks the $R_{\theta JC}$ of our Ga_2O_3 SBDs against commercial 600-V SiC SBDs with a similar current rating and different TO-series packages. The $R_{\theta JC}$ of our junction-side cooled Ga_2O_3 SBD is lower than that of the commercial SiC SBDs with similar package size and current rating. This shows the low k_T of Ga_2O_3 can be overcome by packaging solutions.

[1] APL, vol. 115, no. 26, p. 263503, 2019.

[2] IEEE EDL, vol. 42, no. 8, pp. 1132-1135, 2021.

4:30pm **DI-TuA-12 High Temperature In-situ MOCVD-grown Al_2O_3 Dielectric on (010) β-Ga_2O_3 with 10 MV/cm Breakdown Field**, ***Saurav Roy,*** University of California Santa Barbara; *A. Bhattacharyya,* University of Utah; *C. Peterson, S. Krishnamoorthy,* University of California Santa Barbara

We report on the growth and characterization of in-situ Al_2O_3 on (010) β-Ga_2O_3 using metalorganic chemical vapor deposition (MOCVD). The in-situ Al_2O_3 deposition provides an in-situ passivation to the underlying epitaxial β-Ga_2O_3 layer and protects the semiconductor surface from undesired contaminants. The MOCVD growth of Al_2O_3 also facilitates high temperature dielectric deposition compared other conventional techniques, which is known to enhance the bulk and interface quality of the dielectric. The growth of β-Ga_2O_3 was performed in an Agnitron MOVPE reactor with far injection showerhead design using Triethylgallium and Oxygen as precursor gas at a growth temperature of 600 ^{0}C, which is followed by the growth of Al_2O_3 layer at the growth temperature of 810 ^{0}C inside the same chamber using Trimethylaluminum and O_2 as precursors without breaking the vacuum. Thickness of the grown Al_2O_3 layer was extracted to be 23 nm using Xray reflectivity measurements. Using capacitance voltage (CV) measurements, the dielectric constant of the Al_2O_3 layer was extracted to be ~8. The fast and slow near interface traps at the in-situ Al_2O_3/ β-Ga_2O_3 interface were characterized using stressed CV measurements on metal oxide semiconductor capacitor (MOSCAP) structures. The sheet density of near interface trap states with fast and slow emission times were also calculated to be 8.3 x 10^{11} cm^{-2} and 1.5 x 10^{11} cm^{-2} respectively. The density of the interface states (initially filled and unfilled) and bulk oxide hole traps (D_t) and their energy dependences were calculated to be 5.4 x 10^{11} cm^{-2} eV^{-1} using deep ultra-violet assisted CV technique, which is significantly lower than the ALD Al_2O_3/β-Ga_2O_3 interface from literature. Furthermore, the breakdown voltage and leakage currents for the in-situ Al_2O_3/β-Ga_2O_3 MOSCAPs were evaluated using forward and reverse IV characteristics. In the accumulation regime with forward bias, the entire electric field drops across the oxide layer. An average peak breakdown field of approximately 10.2 to 10.6 MV/cm underneath the center of the anode is evaluated. High breakdown field in combination with a dielectric constant close to β-Ga_2O_3, makes this an excellent dielectric/semiconductor platform for high performance device applications. This approach of in-situ dielectric deposition on β-Ga_2O_3 can pave the way as gate dielectrics for future β-Ga_2O_3 based high performance MOSFETs due to its promise of improved interface and bulk quality compared to other conventional dielectric deposition techniques. We acknowledge funding from AFOSR MURI program under Award No. FA9550-21-0078 (PM: Dr. Ali Sayir).

4:45pm **DI-TuA-13 Metal Oxide (PtOX) Schottky Contact with High-k Dielectric Field Plate for Improved Field Management in Vertical β-Ga2O3 Devices**, ***Esmat Farzana,*** University of California Santa Barbara; *A. Bhattacharyya,* The University of Utah; *T. Itoh, S. Krishnamoorthy, J. Speck,* University of California Santa Barbara

β-Ga_2O_3 has emerged interest in high-power electronics due to its high breakdown field (8 MV/cm) and melt-grown substrates. To extract the full potential of β-Ga_2O_3 devices, high reverse blocking capability and field management are fundamental requirements. However, this is challenging in β-Ga_2O_3 due to absence of its p-type that limits high barrier formation in critical field regions. Hence, to enhance the β-Ga_2O_3 diode performance, it is important to have high Schottky barrier material at surface as well as efficient field-plate dielectric. Toward this goal, we developed metal oxide (PtO_x) Schottky contact with high-κ dielectric (ZrO_2) field plate in vertical β-Ga_2O_3 devices to support high electric field at both surfaces and edges. Vertical field-plate Schottky diodes were fabricated at UCSB with HVPE (001) 10 μm β-Ga_2O_3 epitaxy (doping ~2×10^{16} cm^{-3}). The devices had Ti/Au ohmic and Pt cap/PtO_x Schottky of 100 μm diameter. The PtO_x was formed by reactive sputtering of Pt and oxygen. The field plates were investigated with different lengths, 15 μm and 30 μm, with sputter deposited dielectric ZrO_2 (~215 nm). The ZrO_2 was chosen for its ~1.2 eV conduction band offset with β-Ga_2O_3, breakdown field >3 MV/cm, and dielectric constant of ~23. The PtO_x Schottky properties were first characterized with current-voltage (I-V) and capacitance-voltage (C-V), and compared with that of Pt/β-Ga_2O_3 from the same HVPE β-Ga_2O_3 sample. The PtO_x Schottky had a significantly higher barrier height of ~2.1 eV from both I-V and C-V compared to that of Pt with 1.35 eV (I-V)/ 1.6 eV (C-V). The similar barrier height for PtO_x from I-V and C-V indicates its homogeneous interface. The forward current of the field-plate PtO_x diodes also showed near unity ideality factor (1.17) and on-off ratio of ~10^{11}. The minimum specific on-resistance of the PtO_x diodes was 2.6, 2.36, and 2.3 mΩ-cm^2 for devices without field plate, with field plate lengths of 15 μm, and 30 μm respectively. The reverse breakdown of the diodes was characterized at the Univ. of Utah. A maximum breakdown voltage (V_{br}) of 947 V was obtained with 30 μm field plate whereas the diode with 15μm field plate and without field plate showed V_{br} of 882 V and 520 V, respectively. The consistent increase of V_{br} with field plates indicates their field management efficacy. SILVACO simulation showed a peak electric field of 5.12 MV/cm in β-Ga_2O_3 and 3.5 MV/cm in ZrO_2 at V_{br}~950V. The BFOM (0.4 GW/cm^2) of our diodes is comparable or better than most of the reports. As the ZrO_2 breakdown limited to reach the full potential of β-Ga_2O_3, future work will include high breakdown dielectric to further improve the device performance.

5:00pm **DI-TuA-14 Field Plated β-Ga_2O_3 Mis Diodes with High-κ Tio_2 Interlayer for Increased Breakdown and Reduced Leakage Current**, ***Nolan Hendricks,*** Air Force Research Laboratory; UC Santa Barbara; *A. Green, A. Islam, K. Leedy, K. liddy, J. Williams,* Air Force Research Lab; *E. Farzana, J. Speck,* UC Santa Barbara; *K. Chabak,* Air Force Research Lab

β-Ga_2O_3 (BGO) is an ultra-wide bandgap (~4.8 eV) semiconductor with disruptive potential for power electronics due to its predicted breakdown field of 8 MV/cm, ease of n-type doping, and availability of melt-grown native substrates. With no p-type doping, Schottky barriers are essential to limit reverse leakage current in rectifying BGO devices. However, reverse leakage current due to thermionic field emission in such devices exceeds the practical limit of 1 mA/cm^2 at surface fields ($\mathcal{E}_{surf}$) <5 MV/cm for barrier heights <2.2 eV, limiting the potential benefits of BGO. It is desirable to find a solution for reducing leakage current in diodes without efficiency losses from increased turn-on voltage (V_{on}) or specific on-resistance ($R_{on,sp}$). TiO_2 is a high κ (~60) dielectric with a conduction band edge ~0.3 eV *lower* than BGO, presenting the potential for use in metal-interlayer (MIS) diodes to provide a wider tunneling barrier with no increased barrier height for forward conduction.

Pt/TiO_2/β-Ga_2O_3 MIS diodes and Schottky barrier diodes (SBDs) with and without field plates were fabricated on ~5 μm, 6x10^{16} cm^{-3} (001) HVPE BGO on an n+ BGO substrate. A back side Ti/Au contact was RTA annealed at 470 °C for 60 s in N_2 ambient. TiO_2 (4.5 nm) was deposited by atomic layer deposition and removed with BOE in areas for SBDs. Pt/Au anode contacts were deposited, followed by 200 nm PECVD SiO_2 and Ti/Au field plate metal with 20 μm overhang.

Forward current-voltage (I-V) behavior was measured for all device types. An ideality factor of 1.08 and 1.09 was fitted for SBDs and MIS diodes respectively. The minimum differential $R_{on,sp-}$ was ≤1.2 mΩ·cm^2 in all devices, and V_{on} extrapolated from the linear I-V was similar between the SBDs and MIS diodes at 1.4 V.

The leakage current and breakdown of the devices were measured under reverse bias. The SBDs experienced catastrophic breakdown at 453 V (no FP) and 495 V (FP), and both reached 1 mA/cm^2 leakage current at 235 V, corresponding to an $\mathcal{E}_{surf}$ of 2.3 MV/cm. The MIS diodes experienced breakdown at 552 V (no FP) and 666 V (FP). 1 mA/cm^2 leakage current was observed at 408 V (no FP) and 574 V (FP), with corresponding $\mathcal{E}_{surf}$ estimated to be 3.0 MV/cm and 3.5 MV/cm respectively. The BFOM of the field plated MIS diode was 370 MW/cm^2 for hard breakdown and 270 MW/cm^2 when limited to 1 mA/cm^2 leakage current, both of which are the best reported in their respective categories for BGO MIS diodes. The substrate resistance is expected to be ~0.9 mΩ·cm^2, so similarly fabricated devices with lower parasitic resistance are expected to achieve a BFOM >1 GW/cm^2 with leakage <1 mA/cm^2.

Epitaxial Growth
Room Jefferson 2-3 - Session EG-TuA
Bulk & Epitaxy II

Moderator: Xiuling Li, University of Texas Austin

1:45pm **EG-TuA-1 Progress in Beta-Gallium Oxide Materials and Properties**, ***James Speck,*** University of California Santa Barbara **INVITED**

In this presentation, we present recent work on the development of β-Ga_2O_3 materials and their properties. The talk will include the following topics:

*Coherently strainedβ-$(Al_xGa_{1-x})_2O_3$ thin films on β-Ga_2O_3 Part I: Growth of (001) β-$(Al_xGa_{1-x})_2O_3$ thin films via metal oxide catalyzed epitaxy. In this work, we report on the growth of (001) β-$(Al_xGa_{1-x})_2O_3$ films in molecular beam epitaxy via metal oxide catalyzed epitaxy. Films with Al contents up to 15% were grown and Al content was measured with atom probe tomography. A relationship between Al content and out of plane lattice

parameter was determined. Transmission electron microscopy showed no evidence of extended defects in the (001) β-$(Al_xGa_{1-x})_2O_3$ and reciprocal space maps confirmed that the β-$(Al_xGa_{1-x})_2O_3$ films were coherently strained to the (001) β-Ga_2O_3. Sn was also demonstrated to act as a surfactant for (001) β-$(Al_xGa_{1-x})_2O_3$ growth, allowing for high quality, uniform films with smooth morphologies.

*Coherently strainedβ-$(Al_xGa_{1-x})_2O_3$ thin films on β-Ga_2O_3 Part II - composition determination. We derive the relationships between lattice parameters for β-$(Al_xGa_{1-x})_2O_3$ and Al content x assuming the β-$(Al_xGa_{1-x})_2O_3$ is coherently strained to β-Ga_2O_3. The fundamental stiffness tensor of β-$Ga_2O_3$and stress-strain relationships are used to determine out of plane lattice parameters for (010) and (001) β-$(Al_xGa_{1-x})_2O_3$. Additionally, transformation of the stiffness tensor allows for derivation of similar relationships for (100) β-$(Al_xGa_{1-x})_2O_3$. For all three orientations, the relationships between peak spacing for β-$(Al_xGa_{1-x})_2O_3$ and β-Ga_2O_3 peaks in HRXRD and Al content x are calculated.

*We describe two recent ultrafast optical pump probe experiments that have determined the electron-phonon scattering time - 4.5 fs for electron-polar optical phonon scattering. These experiments also determined the energy separation of the CBM to the first side valley: 2.6 eV [Marcinkevicius et al., Appl. Phys. Lett. **118**, 242107 (2021)]. In a separate ultra-fast pump probe spectroscopy study, the time scale for the formation of polarons (from optically generated free holes) was determined: 0.5 to 1.1 ps [[Marcinkevicius et al., Appl. Phys. Lett. **116**, 132101 (2020)].

2:15pm **EG-TuA-3 (110) β-Ga_2O_3 Epitaxial Films Grown by Plasma-Assisted Molecular Beam Epitaxy**, ***Takeki Itoh**, A. Mauze, Y. Zhang, J. Speck,* University of California at Santa Barbara

Epitaxial growth of β-Ga_2O_3 with superior crystal quality has been achieved on different crystal orientations such as (100), (010) and (-201) via plasma-assisted molecular beam epitaxy (PAMBE)[1]. So far, most of the research has been performed on (010) substrates. However, investigation on (010) substrates has shown that (110) facets are revealed the chevron consistent features in RHEED studies, which indicates (110) is a natural plane in β-Ga_2O_3[2]. Figure 1 shows atomic models of (110) and (010) planes projected along [001] direction.

Unintentionally doped (UID) β-Ga_2O_3 epitaxial films were grown on (110) substrates by PAMBE while (010) substrates were co-loaded as growth reference. The temperatures of the substrates were kept at 600 ℃ and 700 ℃. To optimize the growth condition, the Ga fluxes were changed from 3.0×10^{-8} Torr to 2.5×10^{-7} Torr which were measured by beam equivalent pressure (BEP). Prior to the growth, oxygen polishing and Ga polishing were performed to remove the residual impurities from the surfaces. The film thickness was determined by measuring high-resolution X-ray diffraction (HRXRD). The surface morphology of the epitaxial films was measured by atomic force microscopy (AFM). Figure 2 shows the RHEED pattern of (110) and (010) substrates after Ga polishing. Streaky patterns were observed from the surface of (110) substrates, which indicates atomically flat surface. Conversely, crossed lines (red guideline) corresponding to (110) facets were observed from [001] azimuth on (010) substrate. Figure 3 shows the HRXRD result of the (110) β-Ga_2O_3 epitaxial film. Clear thickness fringes indicate abrupt interface between β-Ga_2O_3 and β-$(Al_{1-x}Ga_x)_2O_3$ spacer layers. Figure 4 shows the growth rate dependence on Ga flux of (010) and (110) substrates at 600 ℃ and 700 ℃. This result suggests that the growth rate is not reduced on the (110) plane compared to (010)[3]. In the oxygen rich regime, the growth rate increases linearly with Ga flux. In the plateau regime, there was still too low excess Ga flux to have a reduced growth rate. We expect higher Ga flux to yield reduced growth rates. Figure 5 shows the surface morphology of β-Ga_2O_3 films grown at 700 ℃ on (110) and (010) substrates. The RMS values indicate smooth surface morphology was obtained by growing on (110) substrates. Despite the appearance of (110) facets in the growth of (010) β-Ga_2O_3, the (110) plane does not have the tendency to show a well-defined step-terrace structure.

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2:30pm **EG-TuA-4 Si-doped β-Ga2O3 Films Grown at 1 µm/hr by Suboxide MBE**, ***Kathy Azizie**, P. Vogt, F. Hensling, D. Schlom, J. McCandless, H. Xing, D. Jena,* Cornell University*; D. Dryden, A. Neal, S. Mou, T. Asel, A. Islam, A. Green, K. Chabak,* Air Force Research Laboratory

In this work we further develop suboxide molecular-beam epitaxy (S-MBE) to establish a means to Si-dope β-Ga2O3 grown by S-MBE and investigate its electrical properties. S-MBE was recently shown to enable the growth of β-Ga2O3 at growth rates exceeding 1 µm/hr with excellent crystallinity, surface smoothness, and at a low growth temperature. The key concept of S-MBE is to eliminate the first step of the two-step reaction mechanism involved in the growth of β-Ga2O3 by conventional MBE. In S-MBE, pre-oxidized gallium in the form of a molecular beam that is 99.98% Ga2O, i.e., gallium suboxide, is supplied. By eliminating the rate limiting step of conventional MBE—the oxidation of gallium to its suboxide—we achieve higher growth rates and avoid the etching that occurs in the conventional MBE growth of Ga2O3 at high fluxes of metallic gallium. Building upon S-MBE, we have studied Si-doped β-Ga2O3 films while maintaining a 1 µm/hr growth rate and high quality crystallinity, as confirmed by x-ray diffraction (XRD), atomic force microscopy (AFM), and reflection high-energy electron diffraction (RHEED). We investigate the incorporation and electrical properties of Si-doped β-Ga2O3 films using a variety of Si-based sources, including suboxide sources, with the goal of achieving replicable and controllable Si-doped β-Ga2O3 in the 1016 to 1018 cm-3 regime. The concentration of silicon incorporated as well as impurities present in the films are measured by secondary ion mass spectroscopy (SIMS). The electrical mobility and mobile carrier concentration is assessed by the Hall effect, including temperature-dependent Hall measurements. We have also fabricated and tested MESFETs from Si-doped β-Ga2O3 films grown by S-MBE at growth rates of 1 µm/hr.

2:45pm **EG-TuA-5 MOCVD Growth of Ga_2O_3 and $(Al_xGa_{1-x})_2O_3$**, ***Hongping Zhao**,* The Ohio State University **INVITED**

Ultrawide bandgap (UWBG) gallium oxide (Ga_2O_3) represents a promising semiconductor material with excellent chemical and thermal stability. Its wide energy bandgap (4.5-4.9 eV) predicts a breakdown field of 6-8 MV/cm, which is much larger than that of the 4H-SiC or GaN. The key advantages from this material system arise from the availability of high quality scalable bulk substrate and the capability of a wide range of doping.

Metalorganic chemical vapor deposition (MOCVD) growth technique has been demonstrated to produce high quality β-Ga_2O_3 thin films and its ternary $(Al_xGa_{1-x})_2O_3$ alloys. Record charge carrier mobilities approaching theoretical limit were reported from MOCVD grown materials. In this talk, I will discuss the control of background and n-type doping in MOCVD β-Ga_2O_3, and the impact of metalorganic precursor on Ga_2O_3 growth rate and material quality.

Growth and fundamental understanding of $(Al_xGa_{1-x})_2O_3$ with different phases are still limited. The limit of Al incorporation in beta-phase Ga_2O_3 has not been well understood or experimentally verified, although it was predicted up to 60% of Al composition could be incorporated into β-Ga_2O_3. In this talk, MOCVD growth of β-AlGaO with targeted Al composition of > 40%, n-type doping capability as a function of Al composition in $(Al_xGa_{1-x})_2O_3$, and MOCVD growth of different phase AlGaO will be discussed.

Acknowledgement: The authors acknowledge the funding support from the Air Force Office of Scientific Research FA9550-18-1-0479 (AFOSR, Dr. Ali Sayir) and the National Science Foundation (1810041, 2019753, 1755479).

Epitaxial Growth
Room Jefferson 1 & Atrium - Session EG-TuP
Epitaxial Growth Poster Session

EG-TuP-1 α-phase Gallium Oxide Thin Films Stabilized on a-, r- and m-plane Sapphire Substrates via Reactive Magnetron Sputtering and Pulsed Laser Deposition, ***Edgars Butanovs,*** Institute of Solid State Physics University of Latvia

Gallium oxide Ga_2O_3 has recently attracted a lot of scientific attention as a prospective ultra-wide bandgap semiconductor. It has five different polytypes α, β, δ, γ and ε among which the most studied and thermodynamically stable phase is β-Ga_2O_3. However, corundum-structured α-Ga_2O_3 with 5.2 eV bandgap is a better alternative for power electronics and ultraviolet optoelectronics applications. α-Ga_2O_3 is a metastable phase and it cannot be obtained as bulk crystals used for homoepitaxial growth. On the other hand, sapphire (α-Al_2O_3) is a convenient substrate for heteroepitaxy since some of its crystalline planes have a small lattice mismatch with α-Ga_2O_3, but there are only few and recent reports on the use of other orientation sapphire substrates than c-plane. In this work, we demonstrate growth of α-Ga_2O_3 thin films on a-, r- and m-plane sapphire wafers at various substrate temperatures via two different methods – reactive magnetron sputtering and pulsed laser deposition. Crystalline structure, elemental composition, surface morphology and optical properties were characterized by X-ray diffraction, X-ray photoelectron spectroscopy, scanning and transmission electron microscopy, atomic force microscopy and UV-VIS measurements. α-phase stability dependence on film thickness was also investigated. Such epitaxial stabilization of high-quality thin films with commonly used deposition methods is a perspective way how to integrate α-Ga_2O_3 on available substrates.

The financial support of Latvian Council of Science FLPP project LZP-2020/1-0345 is greatly acknowledged.

EG-TuP-2 Epitaxial Growth of $(Al_xGa_{1-x})_2O_3$ by Suboxide MBE, ***Jacob Steele,*** *K. Azizie, J. McCandless,* Cornell University; *T. Asel,* Air Force Research Lab; *H. Xing, D. Jena, D. Schlom,* Cornell University

Ga_2O_3 has garnered significant interest due in part to its ultra wide bandgap (~4.7ev) and large breakdown field which make it optimal for next-generation power devices. This already exceeds benchmark materials such as SiC and GaN but it is possible to alloy with Al to form $(Al_xGa_{1-x})_2O_3$ and further raise the bandgap up to 8.3 eV, higher than diamond. This can be desirable but presents a challenge for the most commonly researched phase, β-Ga_2O_3, as it is structurally unstable at higher Al concentrations, limiting the range of possible alloying. In contrast, α-phase Ga_2O_3 has been shown to alloy over the full range of x with one technique for growing α-$(Al_xGa_{1-x})_2O_3$ being molecular beam epitaxy (MBE). MBE is a powerful technique with one drawback being its relatively slow growth rate, which has a maximum of roughly 0.2 µm/hour. Fortuitously, the recent development of suboxide MBE, has enabled the epitaxial growth of β-Ga_2O_3 with growth rates exceeding 1 µm/hr without compromising film quality.

This work investigates the application of suboxide MBE to the growth α-$(Al_xGa_{1-x})_2O_3$ thin films. The goal of this project is to determine whether suboxide MBE can grow high quality epitaxial α-$(Al_xGa_{1-x})_2O_3$ over the full range of x with growth rates exceeding 1 µm/hr. For this suboxide MBE study, gallium suboxide and elemental aluminum sources were used and the ozone pressure, growth temperature, Al_2O_3 substrate orientation, gallium suboxide flux, and elemental aluminum flux were varied to map out promising growth conditions. Our experiments reveal that a-plane sapphire substrates consistently enable the epitaxial growth of α-$(Al_xGa_{1-x})_2O_3$ over a broad range of growth conditions. We also show that the growth rates of α-$(Al_xGa_{1-x})_2O_3$ using suboxide MBE approach 1 µm/hr with high surface quality by rocking curves and atomic force microscopy measurements. Lastly, we demonstrate that the aluminum content of the α-$(Al_xGa_{1-x})_2O_3$ films covers a large range of x including the high x values where β-$Ga_2O_3$is unstable.

EG-TuP-5 Free Carrier Control in Homoepitaxial β-Ga_2O_3 Thin Films by Tin Impurity Doping, ***Neeraj Nepal,*** *B. Downey, V. Wheeler, D. Katzer, E. Jin, M. Hardy, V. Gokhale, T. Growden,* US Naval Research Laboratory; *K. Chabak,* Air Force Research Laboratory; *D. Meyer,* US Naval Research Laboratory

Ultra-wide bandgap (UWBG) semiconductors such as c-BN, AlN, high Al content AlGaN, β-Ga_2O_3, anddiamond, with a bandgap greater than 3.4 eV, have higher figures of merit values than GaN and SiC for power and rf devices making them candidates for next generation high-power/temperature electronic materials [1-3]. The availability of inexpensive large-area bulk substrates synthesized by melt growth techniques at atmospheric pressure provides a scaling advantage for β-Ga_2O_3 over other UWBG semiconductors [2]. In addition, homoepitaxial growth on bulk substrates offers the potential of low defect density films for vertical power devices. Further, controlled n-type doping with a shallow donor level (15-50meV [4]) is another advantage of β-Ga_2O_3 compared to AlN and high Al-content AlGaN. For these reasons, homoepitaxial growth of unintentionally- and impurity-doped Ga_2O_3 films and their electrical and structural properties are of great interest.

In this paper, we report MBE growth and Sn impurity doping of β-Ga_2O_3 thin films on (010) β-Ga_2O_3 substrates from Novel Crystal Technology and Northrop Grumman SYNOPTICS vendors. Maintaining smooth surface in in-situ RHEED, the growth rate was increased approximately from 1 to 3nm/min by optimizing the growth conditions such as Ga flux, plasma conditions and growth temperature (T_g). At optimal conditions with a T_g of 725 °C, surface roughness, and X-ray rocking curve full-width at half maximum were about 0.36 nm, and 20 arc-sec for ~390 nm thick films, respectively. Optimal growth conditions that resulted in high structural and surface quality were used to explore doping parameter space using Sn impurity. The Sn cell temperature was varied from 570 to 630 °C to control incorporated Sn concentration and hence free carrier density. Hall effect measurements were carried out on Sn-doped layers using In-dots contacts, and selected samples were processed into van der Pauw Hall measurement structures to verify the In-dot-based Hall effect values. Hall effect measurements demonstrate that free carrier density can be controlled in the range $1x10^{16}$ to $3x10^{19}$ cm^{-3}. A mobility of 49 cm^2/V-s with free carrier density of $3x10^{19}$ cm^{-3} was measured which is comparable to the previously reported values for Sn-doped β-Ga_2O_3 [5].

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EG-TuP-6 MBE Growth of Doped and Insulating Homoepitaxial β-Ga_2O_3, ***Jon McCandless,*** *V. Protasenko, B. Morell,* Cornell University; *E. Steinbrunner, A. Neal,* Air Force Research Laboratory, Materials and Manufacturing Directorate, USA; *Y. Cho, N. Tanen, H. Xing, D. Jena,* Cornell University

The group IV atoms Si, Ge, and Sn have been investigated as *in-situ* n-type dopants in the molecular beam epitaxy (MBE) growth of β-Ga_2O_3. However, it has remained challenging to achieve controllable and intentional n-type doping of low doping densities in MBE due to the tendency of the dopants to oxidize during the growth. As a result, doping is restricted to a small window of growth conditions. Recently, we have overcome this doping challenge by modifying the effusion source design. This modification allowed us to achieve room temperature mobilities of ~130 cm^2/Vs at $1\times10^{17}/cm^3$ with Si doping.

Variations in the transport measurements between samples doped under similar conditions was observed. For example, some unintentionally doped samples (UID) exhibit electrically insulating behavior in Hall effect measurements, while others exhibit measurable conductivity. Secondary ion mass spectrometry (SIMS) measurements revealed that Si, which is universally observed at the substrate-film interface, and Fe (the compensating acceptors included in the substrate to make it semi-insulating) varied from sample to sample. Depending on the chosen substrate, this resulted in the variability of the nominal conductivity of UID samples.

To address this it is necessary to grow an additional layer, doped with deep, compensating acceptors, on top of the substrate to compensate the

interface charge. Here we will present our latest research on controllable doping, design of a compensating layer to achieve insulating films, and the impact these have on the growth of field-effect transistors.

EG-TuP-7 High Conductivity Homoepitaxial β-Ga_2O_3 Regrowth Layers by Pulsed Laser Deposition, ***Hyung Min Jeon,*** KBR*; K. Leedy,* Air Force Research Laboratory

With a high critical field strength, wide bandgap, and transparence, β-Ga_2O_3 is a unique material for high power switching and amplifier applications, as well as optoelectronic applications as it is a transparent conductive oxide. In semiconductor devices, doping of the semiconductor is necessary to modulate a semiconductor's electrical properties. Degenerately doped semiconductors have particular use as an ohmic contact regrowth layer. Highly conductive, measured 2323 S/cm (4.3 x10^{-4} Ω-cm resistivity), homoepitaxial Si-doped epitaxial β-Ga_2O_3 films by pulsed laser deposition has been fabricated in this work. A commercial pulsed laser deposition system with a KrF excimer laser was used for deposition with a Ga_2O_3 - 1 wt. % SiO_2 target. The base pressure of PLD chamber was 2.66 × 10^{-6} Pa with 55 sccm Ar gas introduced during deposition. The substrate temperature, rotating at 30 º/sec, was 590 ºC. The exceptional electrical properties of the Si-doped epitaxial β-Ga_2O_3 films are 2.24 × 10^{20} cm^{-3} carrier concentration and 64.5 cm^2/Vs Hall mobility. The calculated electrical activation efficiency is 77 % calculated using the Si content from secondary ion mass spectrometry depth profile. For practical use of this highly conductive layer in a semiconductor device, large area deposition uniformly is essential. However, PLD suffers from limitation of scale up area due to the point laser energy source. We found that locally non-uniformed and less-conductive layers cause degradation of the electrical properties in large area film. We examined the growth conditions that address this local conductivity non-uniformity and present solutions using improved deposition parameters.A uniform, low resistivity β-Ga_2O_3 layer is anticipated to enable increased tunneling current between metal contacts and β-Ga_2O_3 transistor channel layers reducing power dissipation and improving overall transistor performance. Moreover, wide bandgap β-Ga_2O_3 with unusually high conductivity can be a suitable candidate for future optoelectronic applications.

EG-TuP-9 Highly conductive β-Ga_2O_3 and $(Al_xGa_{1-x})_2O_3$ epitaxial films by MOCVD, ***Fikadu Alema,*** Agnitron Technology*; T. Itoh, J. Speck,* Materials Department, University of California, Santa Barbara*; A. Osinsky,* Agnitron Technology

We report on the growth of highly conductive (n>1020 cm-3) Si or Ge doped β-Ga2O3 and β-$(Al_xGa_{1-x})_2O_3$ epitaxial films grown on (010) β-Ga_2O_3 substrates by MOCVD. Triethylgallium (TEGa), triethylaluminum (TEAl), and pure oxygen were used as Ga, Al, and O_2 sources. Silane (SiH_4) and germane (GeH_4) diluted in nitrogen were used as sources for Si and Ge. The layers were grown at a lower substrate temperature (~500-600 °C); the effects of O_2 flow, film growth, pressure, and dopant flow rates on the incorporation and activation efficiency of the dopants were studied. By carefully adjusting these process conditions, doping limitations for epitaxial β-Ga_2O_3 and AlGaO alloys with various Al composition were defined. With Si dopant, films with the conductivity of ~2515 S/cm (μ=50.7 cm^2/Vs, n =3.1x10^{20} cm^{-3}) were achieved as determined by Hall effect measurements. This result sets a record compared to the best conductivity value reported in the literature, 2323 S/cm in a layer grown by PLD [1]. Similarly, despite the challenges with Ge doping due to its severe process dependence, highly conductive Ge-doped layers with the conductivity of ~1580 S/cm (μ=38 cm^2/Vs, n = 2.6x10^{20} cm^{-3}) were realized. Temperature-dependent Hall measurement showed no charge density dependence on temperature both for heavily Ge and Si-doped films, indicating degenerate doping. The heavy Si doping process developed for β-Ga_2O_3 has also been extended to β-$(Al_xGa_{1-x})_2O_3$ with varying Al content. The AlGaO layer thickness and Al content in the films were estimated by HRXRD measurement, while Hall effect measurements were used to study the electrical characteristics of the layers. For coherently strained, ~70-75 nm thick, AlGaO layers with Al content of 12.3%, films with a conductivity of 612 S/cm (μ=31.1 cm^2/Vs, n =1.23x10^{20} cm^{-3}) were achieved. However, this value was reduced to ~220 S/cm (μ=25 cm^2/Vs, n =5.5x10^{19} cm ^{3}) when the Al content increased to 22%. The effects of AlGaO layer thickness and Al content on Si incorporation, surface roughness, free carrier concentration, and electron mobility in AlGaO were studied and will be discussed. The high free carrier concentration in Ga2O3 and AlGaO thin films achieved by MOCVD at low epitaxial growth temperature enables low resistance ohmic contact layers to realize high-performance β-Ga_2O_3 and β-$(Al_xGa_{1-x})_2O_3$/β-Ga_2O_3 heterostructure devices [2].

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Material and Device Processing and Fabrication Techniques
Room Jefferson 1 & Atrium - Session MD-TuP
Material and Device Processing and Fabrication Techniques Poster Session

MD-TuP-1 Record Low Specific Resistance Ohmic Contacts to Highly Doped MOVPE-Grown β-Ga_2O_3 and β-$(Al_xGa_{1-x})_2O_3$ Epitaxial Films, ***Carl Peterson,*** University of California Santa Barbara*; F. Alema,* Agnitron Technology*; S. Roy,* University of California Santa Barbara*; A. Bhattacharyya,* University of Utah*; A. Osinsky,* Agnitron Technology*; S. Krishnamoorthy,* University of California Santa Barbara

We report on the growth and characterization of low resistance ohmic contacts on highly Silicon-doped beta-gallium oxide (β-Ga_2O_3) and pseudomorphic beta aluminum gallium oxide (β-$(Al_xGa_{1-x})_2O_3$) epilayers using metalorganic vapor phase epitaxy (MOVPE). The epitaxial structure consists of Si-doped β-Ga_2O_3 and Si-doped β-$(Al_xGa_{1-x})_2O_3$ epilayers grown on Fe-doped (010) bulk substrates. MOVPE growth was done using Agnitron Technology's Agilis 100 MOVPE reactor with TEGa, O_2, silane (SiH_4), and TEAl as precursors with argon used as the carrier gas. The electrical properties of the Si-doped epilayers are characterized by hall measurements and transfer length measurements (TLM). A 20nm/150nm/50nm Ti/Au/Ni metal stack was deposited via e-beam evaporation and was annealed at 470 °C for 1min. TLM structures were mesa isolated using BCl_3 chemistry-based reactive ion etching process. Four probe current-voltage (I-V) measurements were performed on the TLM structures to obtain the specific contact resistance (ρ_c) of the ohmic contact. Highly linear I-V characteristics were measured on both β-Ga_2O_3 and β-$(Al_xGa_{1-x})_2O_3$. The lowest specific resistance ohmic contact was measured on heavily doped β-Ga_2O_3 with a hall electron concentration of 3.23x10^{20} cm^{-3}. Record low specific contact resistance, as low as 2.3x10^{-7} Ω.cm^2, was measured. This sample had a low sheet resistance of 29.8 Ω/□ which was measured via TLM. The sheet resistances measured through TLM matched with those obtained by hall measurements. For the heavily Si-doped aluminum gallium oxide samples, the lowest specific resistance ohmic contact was measured on a sample with a hall electron concentration of 1.23x10^{20} cm^{-3} and an aluminum composition of 12.3%. Record low specific contact resistance to β-$(Al_xGa_{1-x})_2O_3$, as low as 3.9x10^{-6} Ω.cm^2, was measured on this sample. The low specific resistance also corresponded with the lowest Al composition. Increasing the aluminum composition to 21.6% increased the specific resistance to 4.6x10^{-4} Ω.cm^2. This 21.6% Al sample had an electron concentration of 1.23x10^{20} cm^{-3}. Increasing the aluminum composition in β-$(Al_xGa_{1-x})_2O_3$ also decreased the effectiveness of annealing the Ti/Au/Ni ohmic contacts. Annealing these high aluminum composition samples did not significantly change specific contact resistance and in some cases increased the value of ρ_c. Successful epitaxial growth of highly Si-doped β-Ga_2O_3 and β-$(Al_xGa_{1-x})_2O_3$ films with very low specific contact resistance can facilitate high-performance field-effect transistors.

We acknowledge funding from II-VI Foundation.

MD-TuP-3 MOCVD β-Ga_2O_3 Gate-recessed MESFET, ***Hannah Masten,*** *J. Lundh, J. Spencer,* US Naval Research Laboratory*; F. Alema, A. Osinsky,* Agnitron Technology*; A. Jacobs, K. Hobart, M. Tadjer,* US Naval Research Laboratory

Metalorganic chemical vapor deposition (MOCVD) has shown great potential in growing high-quality epilayer β-Ga_2O_3 films with high growth rates, which will lead to lower cost power electronics [1], [2]. Here, we demonstrate gate-recessed MOCVD metal-semiconductor field-effect transistors (MESFETs) on a 2-inch domestically grown β-Ga_2O_3 substrate.

A 2-inch (010) β-Ga_2O_3 substrate (NG Synoptics) was used for epitaxial growth. The following homoepitaxial structure was grown via Agilis 500 close-injection showerhead MOCVD (CIS-MOCVD) process at Agnitron

Technology: about 1000 nm thick unintentionally doped Ga_2O_3 buffer layer, followed by a 30 nm thick n-type Ga_2O_3 layer (~10^{18} cm^{-3}), and a 10 nm thick n^+ Ga_2O_3 layer for improved channel conductivity and reduced contact resistance. Room temperature Hall measurements indicated a sheet resistance of R_{SH} = 7385 Ω/sq., sheet carrier concentration n_s of 8.68x10^{12} cm^{-2}, with mobility of 97 cm^2/V·s. Mesa isolation was performed via BCl_3 plasma dry etch process (800 W ICP, 60 W RIE, 5 mT, ~30 nm/min). Ohmic contacts were formed via Si ion implantation (3x10^{19} cm^{-3} dose, 100 nm box profile) with an activation anneal of 925 °C for 30 minutes in N_2 atmosphere, followed by lift-off of a 20/200 nm thick Ti/Au metal stack annealed at 475 °C for 1 minute in N_2. This process resulted in a specific contact resistivity of 1.6x10^{-4} Ω/cm^2. An ~15 nm gate recessed was formed via Cl_2 plasma dry etch process (100 W ICP, 150 W RIE, 5 mT, ~15 nm/min). Gate contacts were then formed by lift-off of a 20/200 nm thick Pt/Au metal stack. DC *I-V* measurements were performed on the MESFETs with and without the gate recess etch. Without the gate recess, the MESFETs required a large negative gate bias (V_{GS} = -40 V) to turn off the device due to the highly conductive 10 nm channel. With the 15 nm gate recess, the MESFET is successfully able to turn off at V_{GS} of -10 V. Optimization of the gate recess etch and plasma damage recovery can lead to high-performing, enhancement-mode β-Ga_2O_3 power devices.

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MD-TuP-4 Subsurface Damage Analysis of Chemical Mechanical Polished (010) β-Ga_2O_3 Substrates*, **Michael Liao**, K. Huynh, L. Matto, D. Luccioni, M. Goorsky,* UCLA

The impact of pressure and abrasives on the subsurface damage for chemical mechanical polished (010) β-Ga_2O_3 substrates was assessed. A combination of 1 kPa of applied pressure and colloidal silica was found to be necessary for achieving both smooth surfaces (< 0.5 nm rms) and subsurface-damage-free material. The as-received grounded surfaces of (010) Tamura substrates were lapped and chemical mechanical polished to a damage-free state. Symmetric (020) triple-axis X-ray diffraction rocking curves were employed to assess the subsurface lattice damage by measuring diffuse scatter intensity (i.e. lattice damage from lapping/polishing) quantified by rocking curve widths below the full width at half maximum (FWXM where X < 0.5) [1,2]. The rocking curve FWHM and FW(0.001)M for the as-received ground surface were ~180" and ~8300", respectively. These broad widths correspond to cracks, voids, and dislocations induced by the grinding process. The substrates were lapped with 5 µm alumina particles, then lapped with 0.3 µm alumina particles in water. Colloidal alumina in NaOCl was then used to polish, which was followed by colloidal silica in NaOH. A final cleaning step used abrasive-free diluted bleach and citric acid to remove residual silica on from the surface [3]. Compared to our previous work that used diluted bleach and citric acid to polish various III-V materials [1,2], we show this chemistry combination is inert for β-Ga_2O_3 but is effective in cleaning off colloidal silica particles and other forms of silicon on the substrate surface. The final rocking curve FWHM and FW(0.001)M were ~16" and ~150", respectively after using the colloidal silica, which matches the widths of the as-polished commercial wafers. Material removal rates were measured for each lapping and polishing steps: 5 µm alumina particles yielded a removal rate of ~20 µm/hr, and colloidal silica yielded the slowest ~0.4 µm/hr. The depths of the subsurface damage induced by: lapping with 5 µm alumina particles was ~20 µm and lapping with 0.3 µm alumina was ~6 µm. Determining both the removal rates and depth of subsurface damage is crucial in optimizing lapping and polishing recipes.

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MD-TuP-5 Diffusion of Zn in β-Ga_2O_3*, **Ylva Knausgård Hommedal**, Y. Frodason, L. Vines, K. Johansen,* Centre for Materials Science and Nanotechnology/Dep. of Physics, University of Oslo, Norway

The formation of insulating layers by acceptor dopants is important for β-Ga_2O_3 device fabrication. Commonly used acceptors in Ga_2O_3 are Mg, Cr, Zn and Cu. Typically the acceptors are introduced during growth, or by ion implantation. Acceptor incorporation by indiffusion is also viable but controlling the depth and concentration can be challenging. In this study, we utilize a combination of experimental techniques and first-principles calculations to identify the mechanism for Zn indiffusion, and to assess the prevailing defect configurations and their thermal stability.

Zn has been introduced into (001) and (-201) oriented β-Ga_2O_3 through vapor phase in sealed evacuated quartz ampules heated to temperatures in the range 900-1100°C, for 1 h. The concentration of Zn as a function of depth was measured using Secondary Ion Mass Spectrometry. The Zn concentration was found to reach a value of approximately 10^{20} cm^{-3}, before it drops off abruptly, i.e., the concentration versus depth profile resembles that of a box profile. The profiles were successfully fitted by a trap-limited diffusion model, assuming that interstitial Zn (Zn_i) is the mobile specie, which then is trapped and released through dissociation from a hereto unknown defect. From this model, Zn_i migration barriers of 2.0±0.1 eV and 2.2±0.1 eV were extracted for the (001) and (-201) orientations, respectively, with corresponding dissociation energies of 3.2±0.8 eV and 3.0±0.5 eV.

Through first-principles calculations it was found that the Zn_i donor favors a split-interstitial configuration in which it shares a tetrahedral lattice site with Ga. The calculated migration barrier was found to be 2.3 eV in both [001] and [-201] directions, which is in line with the extracted values from the trap-limited model. Ga vacancies are known to trap donor impurities in β-Ga_2O_3 and is a candidate for the trap. However, the Zn_{Ga} acceptor is predicted to have a dissociation energy of 7.0 eV, making it highly stable and unlikely to dissociate once formed. Interestingly, the Zn_{Ga} acceptor can trap a second Zn_i on a Ga site, forming the donor complex Zn_iZn_{Ga}. The dissociation energy of this complex was found to be 3.7 eV. After Zn indiffusion, the samples where highly conductive, suggesting that the dominating defect is a donor, e.g., Zn_iZn_{Ga}. After a second heat treatment at 1000°C under O_2 flow, the samples turned insulating. This is consistent with Zn_iZn_{Ga} donors being the dominant defect after indiffusion, as such complexes would be expected to dissociate during the post-diffusion anneal, leaving behind compensating Zn_{Ga} acceptors.

MD-TuP-6 Initial Nucleation of Metastable γ-Ga_2O_3 During sub-Millisecond Thermal Anneals of Amorphous Ga_2O_3*, **Katie Gann**, C. Chang, M. Chang, D. Sutherland, A. Connolly, D. Muller, R. van Dover, M. Thompson,* Cornell University

Beta-phase gallium oxide (β-Ga_2O_{-3}) is a promising semiconductor for high frequency, high temperature, and high voltage applications. But in addition to the thermodynamically stable β-phase, numerous other polymorphs exist and competition between various phases must be understood to control defects, especially during growth. The phase formation sequence of Ga_2O_3 from amorphous thin films deposited on non-crystalline neutral substrates was determined using lateral-gradient laser spike annealing to temperatures between 500 and 1400 °C on 400 µs to 10 ms timescales (dwell). The resulting thermal anneal and quench (10^4 – 10^6 K/s) induced phase transformations were characterized with optical microscopy, X-ray diffraction, and transmission electron microscopy (TEM) to develop a processing phase diagram. X-ray characterization indicates that the γ-phase, a defect-spinel structure, first nucleates under all annealing time scales for peak temperatures between 650 °C and 800 °C. At peak anneal temperatures above 850 °C, the thermodynamically stable β-phase is observed after quenching to room temperature, with a small two-phase region near the boundary. Cross-sectional TEM at the onset of γ-phase formation shows nucleation near the center of the film with no heterogeneous nucleation at interfaces. For short duration anneals, the β-phase exhibits large grains which become finer and equiaxed for mid-duration anneals, and finally becoming textured for the highest temperatures at the longest dwells. The formation of the γ-phase prior to all β-phase formation, and the time-dependence of the grain structure, indicates that the γ-phase is initially the kinetically preferred phase, and that the subsequent β-phase formation occurs by heterogeneous nucleation at higher temperatures off of existing γ-phase grains. The low surface energy of the γ-phase implied by these results suggests a reason for widely observed γ-phase inclusions in β-phase Ga_2O_3 films grown by a variety of synthesis methods.

MD-TuP-7 Heavily Doped β-Ga_2O_3 Deposited by Magnetron Sputtering*, Adetayo Adedeji,* Elizabeth City State University*; J. Lawson, C. Ebbing,* University of Dayton Research Institute*; J. Merrett,* Air Force Research Laboratory

Epilayer of doped β-Ga_2O_3 films were deposited on 5 mm x 5 mm semi-insulating Fe-doped (010) β-Ga_2O_3 substrates and conducting Sn-doped (-201) β-Ga_2O_3 by magnetron sputtering. Doping of the epilayers was achieved by co-sputtering pure Ga_2O_3 target with Si target or Fe target. Conducting Si-doped and insulating Fe-doped epilayers were achieved at substrate temperature of 570°C during a 2-hour deposition in Ar/O_2 gas mixtures (5% O_2 by flow rate). SIMS analysis indicated that the concentration of dopant can be controlled with the RF power on the targets. Si concentration > 10^{20} cm^{-3} in the epilayer was achieved. Electrical transport measurements showed that the Fe-doped epilayer is insulating with expected high breakdown field strength. At the corners of Si-doped epilayer, Ti/Au contact metals were deposited by magnetron sputtering as well. Hall-Effect measurements at elevated temperatures indicated donor concentration (> 5e18 cm^{-3}) that increases slightly with temperature. Carrier mobility between 40 - 50 cm^2/V·s was measured, and the value decreases slightly with temperature while the resistivity of the films did not change significantly with temperature. However, contact issues were observed at lower temperatures. High resolution x-ray diffraction (XRD) 2q-w, 2q and rocking curve measurements have shown that the epilayers are single crystalline.

MD-TuP-8 Point Defect Distributions in Ultrafast Laser Induced Periodic Surface Structures on β-Ga_2O_3*, D. Ramdin, E. DeAngelis, M. Noor, M. Haseman, E. Chowdhury, **Leonard Brillson**,* Ohio State University

β -Ga_2O_3 has received widespread attention due to its ultrawide bandgap, which can enable applications under extreme conditions. Ultrafast laser irradiation of β -Ga_2O_3 provides a means to explore the response of the material under these extreme conditions, which can generate point defects as well as modify structural features with electronic properties that differ from the pristine surface. However, an understanding of defects generated by femtosecond laser irradiation in the vicinity of laser induced periodic surface structures (LIPSS) remains to be explored. We correlate topographic features with the presence of defects and relative crystallinity using depth- and spatially resolved cathodoluminescence spectroscopy (DRCLS).We also explore how these defects change work function and associated band bending using Kelvin Probe Force Microscopy (KPFM). Defects are found to correlate with crystalline order and near-surface morphology, even in morphologically flat areas, thus a factor in building many applications such as ultrashallow ohmic contacts and quantum dot patterning.

Scanning electron microscopy, AFM, KPFM and DRCLS provide near-nanometer scale depth and spatially resolved information that reveals the interplay between topography, lattice disorder, and defect formation in the vicinity of LIPSS formed by femtosecond laser irradiation. Reduction in crystalline order can be correlated with the concentration of a defect with an ~2.4 eV optical emission but is also suggested to be affected by defects not observed by DRCLS, including a continuum of states increasing towards the band edges, typical of amorphous semiconductors. Thermodynamic calculations currently available suggest oxygen interstitials and divacancy complexes as likely candidates for the ~2.4 eV emission. Furthermore, laterally resolved CLS reveals that defects can be generated even in the region surrounding the LIPSS. KPFM measurements along with spatially resolved CLS reveal differences in the work function and crystalline order between crests and troughs, lending support to the hypothesis that the LIPSS are formed via the diffusion of point defects because of a relaxation of the surface instability caused by ultrafast laser irradiation. These results suggest that defect formation is an intrinsic feature of ultrafast laser irradiation and LIPSS formation in Ga_2O_3, which has extensive implications for both exploring the robustness of this material under extreme conditions as well as for device fabrication involving LIPSS. This work supported by AFOSR grants FA9550-18-1-0066, FA9550-20-1-0278, and FA9550-16-1-0069 and NSF grant DMR-18-00130.

Theory, Modeling and Simulation
Room Jefferson 1 & Atrium - Session TM-TuP

Theory, Modeling and Simulation Poster Session

TM-TuP-1 Simulation Study of Single Event Effects in Ga_2O_3 Schottky Diodes*, Animesh Datta,* *U. Singisetti,* University at Buffalo

β-Ga_2O_3 has attracted high interest in the last decade and emerged as a promising material for next-generation power, GHz power switching, and RF applications. The large bandgap opens its possibilities for potential space applications, as the electron-hole pair generation in radiation (LET) is inversely proportional to the bandgap. Under radiation conditions in space, single event effects (SEE) are a potential reliability issue for devices in space-based RF and power systems. Previous reports have explored SEE burnout in SiC MOSFETs and thus SEE could also be an issue in Ga_2O_3 based devices. To date, there have been no reports of study of SEE in Ga_2O_3 based devices. In this work, we present the SEE effect in Ga_2O_3 Schottky diodes by simulation. 2-D simulations were performed using Silvaco TCAD to investigate the effects of ionizing radiation (measured in LET) under various bias conditions to understand the failure mechanism in the device. Breakdown simulations (V_{br}= 1400 V) show that the anode edge has the highest electric field; thus, it is chosen as the ion strike location in simulations. Under the radiation conditions, the time-dependent simulations show that the current recovers even at 1000 V and 40 MeV/mg/cm^2 LETs; even though the instantaneous peak field exceeds 8 MV/cm. It is noted that higher LETs take a longer time to recover. The heat generated due to ion strikes can also lead to the failure of devices due to thermal effects. The ion strike results in an instantaneous high current density within the device and leads to excessive Joule heating. The thermal effects were studied in Ga_2O_3 diodes with a diamond coating. Below radiation conditions of V=500V and LET=5 MeV/mg/cm^2 the device does not show any signatures of single event burnout (SEB) including thermal effects. At higher voltage bias and high LETs, there are signatures of possible thermal runaway where the temperature rises to a high value but only for a short amount of time and then recovers. The total energy dissipated under the ion strike condition is also calculated by integrating the power density spatially across the ion track. Our results indicate that under similar radiation conditions the power dissipated in b-Ga_2O_3 Schottky diodes is lower compared to the experimental data of SiC Schottky diodes. Future work includes investigating the threshold condition of SEB in b-Ga_2O_3 Schottky diodes for potential applications in harsh radiation conditions.

TM-TuP-2 Anisotropic Photoresponsivity and Deviation from Beer-Lambert Law in Beta Gallium Oxide*, Md Mohsinur Rahman Adnan,* *D. Verma, S. Dhara,* The Ohio State University*; C. Sturm,* Universitat Leipzig, Germany*; S. Rajan, R. Myers,* The Ohio State University

Polarization-dependent photoresponsivity measurements on (001) β-Ga_2O_3 are modeled by calculating the anisotropic absorption process via the dielectric tensor[1]. Quasiparticle band structure calculations show that three different transitions from topmost group of O^{2-} 2p valance bands to the lowest Ga^{3+} 4s conduction band can occur that contribute significantly to the excitonic spectra[2]. A linear polarizer is utilized in the excitation path to generate photocurrent in (001) β-Ga_2O_3 Schottky diode. Three excitonic transitions corresponding to P_x, mixed P_x/P_z and P_y valance band sates are observed as peaks in the measured photoresponsivity spectra at 4.9eV, 5.2eV and 5.5eV[2]. The intensity of the peaks depends on the linear polarization of the excitation.

This strongly anisotropic absorption process in β-Ga_2O_3 cannot be modeled using a generic absorption coefficient; the Beer-Lambert law is not strictly accurate in an anisotropic dielectric. To model anisotropic absorption, we solve the electromagnetic wave equation using the Berreman[3] matrix and the measured dielectric tensor of β-Ga_2O_3[1]. The Poynting vector versus the linear polarization of the excitation with respect to the a- and b- axes and absorption depth is calculated and used to determine the generation rate and the photoresponsivity spectrum of β-Ga_2O_3. The modeled photoresponsivity matches the experimentally measured 3-peak spectrum and its variation with polarization angle. The simulations confirm that the photon flux in β-Ga_2O_3 over the energy range of interest (4-6eV) does not decay exponentially with depth over the photocarrier collection region, in violation with the Beer-Lambert law.

The exciton Franz Keldysh effect is observed in the photoresponsivity spectra, where exciton absorption peaks red shift with reverse bias[4]. The magnitudes of red shift for the three photoresponsivity peaks are inversely related to the corresponding interband transition energies i.e. the smallest

energy transition peak shows the highest amount of red shift. We will discuss the polarization anisotropy of the field-dependent red-shift in terms of the exciton wave function anisotropy and its impact on the Stark shift.

[1]C. Sturm et al., APL Mater. 3, 106106 (2015).
[2]J. Furthmüller et al., Phys. Rev. B 93, 115204 (2016).
[3]D. W. Berreman, J. Opt. Soc. Am. 62, 4, pp. 502-510 (1972).
[4]M. M. R. Adnan et al., Phys. Rev. Appl. 16, 034011 (2021).

TM-TuP-4 Self-Trapped Holes and Polaronic Acceptors in Ultrawide Bandgap Oxides*, **John Lyons**,* US Naval Research Laboratory

Although Ga_2O_3 is widely believed to be the most promising ultrawide-bandgap semiconductors, its inability to be *p*-type doped hampers its future applications. Recently, other oxide materials have emerged as potential competitors to Ga_2O_3, but their propensity for hole conductivity is less well known. Here the stability of hole polarons in a set of ultrawide-bandgap oxides (Ga_2O_3, Al_2O_3, $ZnGa_2O_4$, $MgGa_2O_4$, $LiGaO_2$ and GeO_2) is examined and compared, both in pristine material and in the presence of acceptor impurities. Holes spontaneously self-trap in all oxides investigated here, with varying stability. Acceptor impurities further stabilize these trapped holes, leading to large acceptor ionization energies. Hole trapping also leads to characteristic distortions and distinct optical transitions, which may explain some experimentally-observed signals. These results indicate that achieving *p*-type conductivity in any of these oxides is unlikely.

This work was supported by the ONR/NRL 6.1 Basic Research Program.

TM-TuP-5 Modeling for a High-Temperature Ultra-Wide Bandgap Gallium Oxide Power Module*, **Benjamin Albano**,* Virginia Tech Center for Power Electronics Systems*; B. Wang, C. DiMarino, Y. Zhang,* Virginia Tech Center for Power Electronics

The ultra-wide bandgap (UWBG) of Ga_2O_3 allows it to achieve over 10-times lower intrinsic carrier concentration than Si permitting Ga_2O_3 devices to operate at much higher temperatures. However, its low thermal conductivity and the associated self-heating could cause the device to exceed its safe operating temperature as prescribed by gate dielectric and packaging material limitations. The objective of this study is to develop a physics-based simulation and computation framework for the co-design of Ga_2O_3 devices and packaging.

Table I outlines the benefits and limitations of different models that are conventionally used for device and packaging design. In the design of the package and the micro-/nano-scale device structures, it is critical to observe the interactions between the two [1] [2]. The traditional package-level FEA simulation usually assumes a uniform power density and junction temperature in the devices, while neglecting the temperature variations in the sub-micron device structures; this variation can be up to tens of kelvin under high-power device operations. Conversely, the typical physics-based TCAD simulation accurately models the electrothermal behaviors within the device but the high computational power required (due to the large difference in length scales between the electrically active regions and the thermal diffusion regions) limits their use when package components need to be considered. These models instead simplify the packaging into nominal boundary thermal resistances, neglecting larger packaging elements in the heat flow path that are critical to overall thermal management and reliability [3].

The simple bottom-side cooled diode shown in Fig. 1. was modeled in ANSYS Workbench, Silvaco 2D TCAD, and Silvaco 3D TCAD. As can be seen in Fig. 2., there were stark differences in the heat distribution between the models. These hot spots are severe reliability liabilities and would need to be accounted for in the package design.

In order to build a platform that accounts for the additional electro-thermal effects while still being practical and efficient, a series of models were built to integrate the physics-based material/device-level simulation with a package-level FEA simulation. These models were then evaluated against more traditional methods of device-package simulation, seen in Table II, to understand the potential benefits of such a method. In end effect, this method would guide both device and package design with the hope of identifying and optimizing the thermal and electric field management needs.

[1] IEEE EDL, vol. 90, no. 6, p. 1065-1076, 2002.

[2] IEEE WiPDA, 2018 p. 287-294.

[3] APL, vol. 115, no. 173508, 2019.

TM-TuP-6 Atomic Surface Structure of Sn doped β-Ga_2O_3(010) Studied by Low-energy Electron Diffraction*, **Alexandre Pancotti**,* Universidade Federal de Jataí, Brazil*; J. T. Sadowski,* Center for Functional Nanomaterials, Brookhaven National Laboratory*; A. Sandre Kilian,* Universidade Federal de Jataí, Brazil*; D. Duarte dos Reis,* Universidade Federal do Mato Grosso do Sul, Brazil*; C. Lubin,* SPEC, CEA, CNRS, Université Paris-Saclay, CEA Saclay , France*; A. Boucly,* SPEC, CEA, CNRS, Université Paris-Saclay, France*; P. Soukiassian,* SPEC, CEA, CNRS, Université Paris-Saclay, CEA Saclay, France*; J. Boeckl, D. Dorsey ,* Air Force Research Laboratory*; M. Shin, T. ASEL,* Air Force Research Lab*; J. Brown, N. Barrett ,* SPEC, CEA, CNRS, Université Paris-Saclay, CEA Saclay , France*; T. Back,* SPEC, CEA, CNRS, Université Paris-Saclay, CEA Saclay

The surface crystallographic and electronic structure of bulk single crystals of transparent, wide gap semiconductor gallium oxide β-Ga_2O_3(010) has been studied using Spot Profile Analysis Low-Energy Electron Diffraction (SPA-LEED) and X-ray Photoelectron Spectroscopy (XPS). The XPS measurements show typical spectra for Ga_2O_3(010). The surface structure of Sn doped single crystal β-Ga_2O_3 Using quantitative LEED I-V. The surface shows a (1 x 1) LEED pattern without reconstruction. The comparison between experimental I-V curves and theoretical LEED simulations using Green's function formalism indicates the formation of a single surface termination layer. There are significant displacements in the first topmost slab surface, moreover, experiment and theory suggest important atomic rumpling between gallium and oxygen atoms in the topmost surface layers. The surface structure agrees with that predicted by first-principles density functional theory calculations and X-ray photoelectron diffraction.

Electronic and Photonic Devices, Circuits and Applications
Room Jefferson 2-3 - Session EP1-WeM

Process & Devices III

Moderator: Uttam Singisetti, University of Buffalo, SUNY

9:15am **EP1-WeM-4 Remarkable Improvement of Conductivity in B-Ga_2O_3 by High-Temperature Si Ion Implantation**, ***Arka Sardar**, T. Isaacs-Smith, S. Dhar,* Auburn University*; J. Lawson, N. Merrett,* Air Force Research Laboratory, USA

Monoclinic Beta Gallium Oxide (β-Ga_2O_3) is emerging as a promising wide bandgap semiconductor for high voltage electronics. Ion implantation is a key process for device fabrication as it provides a unique way to carry out selective area doping with excellent control. It has been demonstrated that Si implantation into (010) β-Ga_2O_3 at room temperature followed by annealing at ~1000°C, results in an activation efficiency (η)of 63% for Si concentrations up to ~5e19 cm^{-3}. However, for higher concentrations, a severe drop of the η to 6% occurs [1]. In this work, we demonstrate that high-temperature implantation can be used to significantly improve this for heavily implanted β-Ga_2O_3. In the case of SiC, implantation at > 500°C results in superior conductivity due to lower defect densities and better recrystallization after annealing [2]. Based on this, we performed room temperature (RT, 25°C) and high temperature (HT, 600ºC) Si implants into MBE grown 300 nm (010) β-Ga_2O_3 films with energies of 275 keV and 425 keV through ~110 nm Mo and ~30 nm Al_2O_3 layers; with a total of fluence of 2.4e15 cm^{-2} or 4.8e15 cm^{-2}. This was followed by annealing in flowing nitrogen at 970ºC for 30 minutes to activate the dopants. SIMS shows the Si profile is ~400 nm deep with an average concentration of ~6.0e19 cm^{-3} for the lower fluence samples, and expected to be ~1.2e20cm^{-3} for the higher fluence (SIMS ongoing). No significant difference in surface roughnesses were detected by AFM throughout the process. HRXRD shows structural defects after the implantation and partial crystallization recovery upon annealing, where the advantage was in favor of HT implantation. The ratio of the free electron concentration from Hall measurements and the total amount of Si in β-Ga_2O_3 was used to determine the activation efficiencies. For the lower fluence, the HT sample shows only a ~6% improvement of η over the RT sample. Remarkably, for the higher fluence, while the RT sample was too resistive for measurement, the HT sample had η close to 70%, with a high sheet electron concentration of 3.3e15 cm^{-2} and excellent mobility of 92.8 cm^2/V·s at room temperature. These results are highly encouraging for achieving ultra-low resistance heavily doped β-Ga_2O_3 layers using ion implantation, which will be discussed further in this presentation.

References:

[1]K. Sasaki et.al,, Appl. Phys. Express 6, 086502 (2013).

[2]F. Roccaforte, et. al, , Micro 2, 23 (2022).

Acknowledgments:

We acknowledge the support of the Department of Physics, Auburn University.

9:30am **EP1-WeM-5 Towards Lateral and Vertical Ga_2O_3 Transistors for High Voltage Power Switching**, ***Kornelius Tetzner**, J. Würfl, E. Bahat-Treidel, O. Hilt,* Ferdinand-Braun-Institut, Leibniz-Institut für Höchstfrequenztechnik (FBH), Germany*; Z. Galazka, S. Bin Anooz, A. Popp,* Leibniz-Institut für Kristallzüchtung (IKZ), Germany **INVITED**

Gallium Oxide (Ga_2O_3) power switching devices are expected to boost efficiency of power converters predominately operating at comparatively high bias voltage levels in the kV range. Thanks to the extraordinarily high energy band gap of 4.9 eV a high device breakdown strength of about 8 MV/cm is expected. Thus it is possible to efficiently utilize these properties for very compact power devices with aggressively minimized gate to drain separation. This enables low resistive on-state and low leakage off-state properties. Most Ga_2O_3 devices introduced so far rely on volume electron transport properties; only a few 2DEG devices have been demonstrated. In any case the values of electron mobility and saturation velocity in Ga_2O_3 crystals may depend on crystal orientation and did not yet reach properties being comparable to more developed wide band gap semiconductor families such as GaN and SiC. – Nevertheless the benefit of Ga_2O_3 devices relates to the combination of high breakdown field and electron transport properties and the resulting compact device design strategies are already getting competitive to existing power switching technologies.

The presentation will give an overview on the current status of lateral and vertical Ga_2O_3 devices with a special emphasis on results obtained at FBH and IKZ [1]. For both cases concepts for epitaxial layer structures and device designs suitable for reaching the targeted performance will be discussed especially in terms of breakdown voltage and channel current density. Critical points for device optimization such as type of gate recess in lateral transistors and concepts of critical electric field reduction in vertical transistors will be addressed.

[1] K. Tetzner, IEEE Electron Device letters, vol. 40, No. 9, (2019), pp. 1503 - 1506.

10:00am **EP1-WeM-7 Comparison of β-Ga_2O_3 Mosfets With TiW and NiAu Metal Gates for High-Temperature Operation**, ***Nicholas Sepelak**,* KBR, Wright State University*; D. Dryden,* KBR*; R. Kahler,* University of Texas at Dallas*; J. William,* Air Force Research Lab, Sensors Directorate*; T. Asel,* Air Force Research Laboratory, Materials and Manufacturing Directorate*; H. Lee,* University of Illinois at Urbana-Champaign*; K. Gann,* Cornell University*; A. Popp,* Leibniz-Institut für Kristallzüchtung, Germany*; K. Liddy,* Air Force Research Lab, Sensors Directorate*; K. Leedy,* Air Force Research Laboratory, Sensors Directorate*; W. Wang,* Wright State University*; W. Zhu,* University of Illinois at Urbana-Champaign*; M. Thompson,* Cornell University*; S. Mou,* Air Force Research Laboratory, Materials and Manufacturing Directorate, USA*; K. Chabak, A. Green,* Air Force Research Laboratory, Sensors Directorate*; A. Islam,* Air Force Research Laboratory, Sensors Directory

β-Ga_2O_3 offers a robust platform for operation of electronic devices at a high temperature because of its large band gap and low intrinsic carrier concentration. We have recently characterized the high temperature performance β-Ga_2O_3 field effect transistors using different gate metals in vacuum and air ambient at temperatures up to 500 °C.

The devices fabricated using TiW refractory metal gate and Al_2O_3 gate dielectric exhibited stable operation up to 500 ºC in vacuum and up to 450 ºC in air [1]. Transfer (I_{DS}-V_{GS}) characteristics of a device were measured at various temperatures in vacuum and air. Extracted I_{MAX}/I_{MIN} for the vacuum test reduced from ~10^4 to 10^2 as temperature was increased up to 500 ºC. During the vacuum characterization, the contact resistance remained unchanged at all temperatures and, therefore, device characteristics showed no degradation once devices were brought back to RT even after several hours of device operation at 500 °C in vacuum.

The devices, fabricated with Ni/Au gate metal and Al_2O_3 gate dielectric, exhibited stable operation up to 500 ºC in air [2]. The measured I_D-V_D characteristics showed no current degradation up to 450 ºC. At 500 ºC, the device exhibited a drop in I_D; however, device characteristics recovered once the device is brought back to RT, even after 20 hours of device operation at 500 °C.

For tests in air ambient, both Ni/Au and Ti/W devicesobserved an increase in current with temperature due to activation carriers from dopants/traps in the device, however, both exhibited $I_{MAX}/I_{MIN} < 10^2$ at 450 ºC because of contact degradation. The barrier height of ϕ_B~ 1.0 eV and 0.77 eV was calculated for the TiW/Al_2O_3 and the NiAu/Al_2O_3 interfaces, respectively using thermionic emission theory. Thought the values of ϕ_B for the Ti/W contacts was consistent with that expected from the work-function difference between TiW and Al_2O_3, the devices with Ni/Au yielded lower ϕ_B presumably due to the diffusion of Ni and the partial crystallization of the Al_2O_3 dielectric [3]. Our results suggest that with appropriate choice of metals and gate dielectrics, the stable 500 ºC operation using β-Ga_2O_3 is achievable.

[1] Sepelak *et al*., "High-temperature operation of β-Ga_2O_3 MOSFET with TiW refractory metal gate," *DRC, 2022*.

[2] Sepelak *et al*., "First Demonstration of 500 °C Operation of β-Ga_2O_3 MOSFET in Air," *CSW, 2022*

[3] Islam et al., "Thermal stability of ALD-grown SiO2 and Al2O3 on (010) β-Ga2O3 substrates," DRC, 2022.

10:15am **EP1-WeM-8 High Electron Mobility Si-doped β-Ga_2O_3 MESFETs**, ***Arkka Bhattacharyya**,* University of Utah*; S. Roy,* University of California at Santa Barbara*; P. Ranga,* University of Utah*; S. Krishnamoorthy,* University of California at Santa Barbara

A hybrid low temperature - high temperature (LT-HT) buffer/channel stack growth is demonstrated using MOVPE with superior carrier mobility values. An LT-grown (600°C) undoped Ga_2O_3 buffer (250-330 nm thick) is grown

followed by transition layers to a HT (810°C) Si-doped Ga_2O_3 channel layers (~220 nm) without growth interruption. The (010) Fe-doped Ga_2O_3 substrates were cleaned in HF for 30 mins prior to channel growth. From Hall measurements, this stack design is shown to have an effective RT Hall mobility values in the range 162 – 184 cm^2/Vs for doped channel electron densities of 1.5-3.5×10^{17} cm^{-3} measured on multiple samples/substrates. These mobility values are higher than the state-of-the-art values in Ga_2O_3 literature. Two types of (010) Fe-doped Ga_2O_3 bulk substrates were used in this study: 5×5 mm^2 diced pieces from 10×15 mm^2 EFG-grown substrates from NCT, Japan and 2-inch CZ-grown bulk substrates from NG Synoptics, USA.

The charge and transport properties were also verified using CV, TLM, field-effect mobility (μ_{FE}) measurements and FET current characteristics. Few samples were processed for regrown ohmic contacts to minimize contact resistance. R_C values of 1-2 Ω.mm were achieved. 3D electron densities were verified by CV measurements. Channel charge profile (from CV) showed the absence of any active parasitic charge below the buffer layer. R_{sh} values from TLM measurements matched closely with Hall measurements. RT μ_{FE} measured on FatFET structures (L_G ~110um, L_{GS}/L_{GD} ~ 1um) showed peak values of 158 and 168 cm^2/Vs in the doped region for electron densities of 3.5×10^{17} cm^{-3} and 2.1×10^{17} cm^{-3} respectively, which are also the highest values to be ever reported. MOSFETs and MESFETs with device dimensions $L_{GS}/L_G/L_{GD}$ = 1/2.5/5 um show max ON currents of ~200 mA/mm and ~130 mA/mm respectively. MESFETs show very high I_{ON}/I_{OFF} ~ 10^{10} and ultra-low reverse leakage. OFF-state voltage blocking capabilities of these devices will be reported.

These buffer-engineered doped high-mobility Ga_2O_3 channel layers with superior transport properties show great promise for Ga_2O_3 power devices with enhanced performance.

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Electronic and Photonic Devices, Circuits and Applications Room Jefferson 2-3 - Session EP2-WeM

Process and Devices IV

Moderator: Christina DiMarino, Virginia Tech

10:45am **EP2-WeM-10 *β*-Ga_2O_3 Lateral FinFETs Formed by Atomic Ga Flux Etching**, ***Ashok Dheenan***, *N. Kalarickal, Z. Feng, L. Meng,* The Ohio State University*; A. Fiedler,* IKZ Berlin, Germany*; C. Joishi, A. Price, J. McGlone, S. Dhara, S. Ringel, H. Zhao, S. Rajan,* The Ohio State University

β-Ga_2O_3 is an ultrawide bandgap semiconductor with attractive properties for high-power electronics including a high theoretical breakdown field of 8 MV/cm and availability of melt-grown substrates. Low room-temperature electron mobility and low thermal conductivity result in both high sheet-resistance and high thermal resistance, limiting field-effect transistor performance. A 'fin' channel structure can overcome these challenges by utilizing a tri-gate geometry to enable electrostatic control over a high sheet-charge density channel while also providing additional surface area for thermal management in the active region. A key process technology for non-planar devices is a low-damage etch method. In this work, we demonstrate *β*-Ga_2O_3 lateral FinFETs with high sheet charge density fabricated with a novel damage-free atomic Ga flux etching technique [N.K. Kalarickal *et* al. APL **119** (2021)]. The epitaxial structure was grown by MOCVD on a (010) Fe-doped semi-insulating substrate. An Mg-doped layer was used to compensate Si donors at the substrate-growth interface to eliminate any parasitic channel. A 500 nm buffer layer was used to isolate the 600 nm Si-doped channel from the Mg and Fe dopants. The process flow started with selective-area MOCVD regrowth of n+ source/drain using a PECVD SiO_2 mask patterned by optical lithography and dry etching. Then a SiO_2 mask for the fins and mesa isolation layer was patterned by electron-beam and optical lithography. The sample was etched by atomic Ga flux -in an MBE chamber. Electron-beam evaporated Ti/Au ohmic contacts were annealed in an N_2 ambient. Ni gates were deposited by RF sputtering. Hall measurements revealed a sheet-charge density of 2.28x10^{13} cm^{-2}, a mobility of 134 cm^2/V.s and a sheet resistance of 1.77 kΩ/sq. Transfer length method showed a contact resistance of 1.27 Ω.mm, a sheet resistance of 2.03 kΩ/sq and a specific contact resistivity of 9.11x10^{-6} Ω.cm^2. C-V measurements at 100 KHz were used to extract a doping density of 6x10^{17} cm^{-3} in the channel. Current density is above 250 mA/mm normalized to the total fin width for a device with a gate length of 1.5 µm and an L_{SD} of 2.5 µm. Transfer characteristics show a threshold voltage of -12 V for a fin width of 200 nm. The on/off ratio of 10^5 is limited by the reverse leakage of the Schottky gate. In summary, *β*-Ga_2O_3 FinFETs with scaled fins were fabricated using novel damage-free Ga flux etching and show promising electrical performance. We acknowledge funding from DOE/NNSA under Award Number(s) DE-NA000392 and AFOSR GAME MURI (Award No. FA9550-18-1-0479, project manager Dr. Ali Sayir).

11:00am **EP2-WeM-11 Insights Into the Behaviour of Leakage Current in Lateral Ga_2O_3 Transistors on Semi-Insulating Substrates***, Z. Chen, A. Mishra, M. Smith, T. Moule,* University of Bristol, UK*; M. Uren,* University of Brsitol, UK*; S. Kumar,* ***Masataka Higashiwaki,*** National Institute of Information and Communications Technology, Japan*; M. Kuball,* University of Bristol, UK

Off-state leakage currents in lateral Ga_2O_3 FET devices have previously been attributed to the presence of unintentional Si (n-type) at the interface between epitaxial grown layer and the substrate [1-4], i.e., a parallel leakage conducting channel. High Fe-doping (>10^{19} cm^{-3}) at the surface of the Ga_2O_3 substrate, followed by thermal annealing, has been shown to compensate the unintentional Si impurities, thereby reducing the leakage current. However, elevated off-state currents and low on-off ratios have still been observed in these devices [4]. Here, we utilize electrical characterization and TCAD simulations to explore the behaviour of leakage current due to Si impurities at the surface of the substrate in lateral Ga_2O_3 transistors.

Lateral Ga_2O_3 transistors studied here were processed on an MBE-grown epitaxial layer on surface-implanted (Fe, p-type) semi-insulating Ga_2O_3 substrates, followed by thermal annealing (more details in ref. 4). The transfer characteristic reveals a pinch-off current (10^{-7}A/mm) with an insensitivity to the gate voltage (Fig 2(a)). The pinch-off current demonstrates ohmic characteristics under opposite drain voltage. The clockwise hysteresis in the C-V and the depletion width (Fig 3) indicate a donor-like trapping effect located near the epitaxy/substrate interface with an activation energy of 0.5eV determined by drain current transients (Fig 4).

2D TCAD simulations (Fig 5), using the SIMS profile for Fe and Si [4] as input parameters, illustrate that the residual Si at the epitaxy/substrate interface pin the Fermi level near the conduction band, resulting in the formation of a parallel conducting channel at the epitaxy/substrate interface (Fig 5(b)). Electrons, from the traps in the epilayer and the contacts, travel vertically to the parallel channel at that interface under negative gate bias. The insensitivity of the leakage current to the gate voltage can be explained by the pinning of the Fermi level due to the high concentration of residual Si dopants. The leakage current magnitude is mostly governed by the resistance of the UID Ga_2O_3 rather than the parallel conduction channel. The latter is evidenced by the constant resistance of the parallel channel in set of circular isolation structures with different spacing (Fig.6). An activation energy of 0.36eV was determined for the leakage current pathway, which contains contributions from the UID layer and the parallel channel (Fig. 7). The mechanism discussed here highlights the role of residual Si contaminants on leakage current. Reduction in their concentration or full compensation is crucial for enhancing performance and device design respectively.

11:15am **EP2-WeM-12 Device Figure of Merit Performance of Scaled Gamma-Gate β-Ga_2O_3 MOSFETs***,* ***Kyle Liddy****, A. Islam, J. Williams, D. Walker, N. Moser, D. Dryden, N. Sepelak, K. Chabak, A. Green,* AFRL

The dynamic switching loss figure of merit ($R_{ON}Q_G$ vs. V_{BK}) is a benchmark used to indicate a device's potential in power-switching applications. Similarly, the lateral Power Figure of Merit ($R_{ON,sp}$ vs. V_{BK}) indicates a devices conduction losses.. This work discusses the fabrication and FOM characterization of optical gate and EBL gate Ga_2O_3 MOSFETs and shows their potential for these application spaces that are currently dominated by other technologies.

A 50 nm Si doped β-Ga_2O_3 channel layer was homoepitaxially grown on a Fe doped (010) substrate by ozone molecular beam epitaxy (MBE) targeting 1.0x10^{18} cm^{-3} carrier concentration. Device fabrication began with mesa isolation using a high-power BCl_3/Cl_2 ICP etch. Contact to the active layer was achieved with a Ti/Al/Ni/Au metal stack deposited by electron beam metal evaporation followed by a 470 ºC anneal in N_2 ambient for 2 minutes. 20 nm of Al_2O_3 gate dielectric was deposited via plasma-enhanced atomic layer deposition. Optical I-gate contacts were defined on half of the sample via optical stepper lithography followed by Ni/Au metal

evaporation. Scaled gamma-gates were defined on the remaining half via electron-beam lithography followed by Ni/Au metal evaporation. Interconnect metal was defined via stepper lithography followed by Ti/Au metal evaporation.

Gate capacitance was collected as a function of gate voltage at a frequency of 1 MHz, and can be seen for the various device types in Figures 2 A and B. Integration over the collected gate voltage range produces the experimentally extracted Q_{GS} of .0014/.0011 and .00082/.00078 nC for the optical and e-beam gate devices respectively. Q_{GD} is calculated assuming maximum depletion of the entire L_{GD}, Using the equation $Q = qN_DAT$. This provides a conservative representation of the total gate charge for these devices when $Q_G = Q_{GS} + Q_{GD}$ of .0060/.0041 nC and .0050/.0034 nC for optical and EBL gate devices respectively. Standard DC I-V device characterization was performed and is shown in Figure 3(A-F).

11:30am **EP2-WeM-13 Electromigration of Native Point Defects and Breakdown in Ga_2O_3 Vertical Devices**, *M. Haseman, D. Ramdin,* Ohio State University*; W. Li, K. Nomoto, D. Jena, G. Xing,* Cornell University*;* ***Leonard Brillson,*** Ohio State University

Beyond the extensive literature on the properties and applications of β-Ga_2O_3 for high power devices, the effects of strong electric fields on the Ga_2O_3 microstructure and in particular the impact of electrically active native point defects have been relatively unexplored.We used cathodoluminescence (CL) point spectra and hyperspectral imaging to observe the spatial rearrangement of oxygen vacancy and vacancy-related defects in Ga_2O_3 vertical trench devices under strong reverse bias.The low crystal symmetry of β-Ga_2O_3 leads to unequal migration of V_O and H-related defects under applied bias resulting in a preferential accumulation of donor species near trench corners where the applied field is strongest, increasing the electric field locally and likely leading to breakdown of the dielectric region.Point defect redistribution along the biasing direction demonstrate post-*operando* the reduced surface electric field (RESURF) effect modulated by the device geometry.

We used CL point spectra and HSI mapping to demonstrate how point defect related donor species in β-Ga_2O_3 vertical Schottky diodes migrate and redistribute under high reverse electrical bias.The accumulation of donor-related defects at Schottky barrier trench corners increases the local doping density and decreases the Ga_2O_3 depletion width such that the electric field falls across a narrower total insulator region, thereby increasing the field locally in the nanoscale trench corner.The low crystal symmetry of the monoclinic crystal structure results in unequal migration energies for point defects on inequivalent lattice sites and along inequivalent crystallographic directions, suggesting a preferential migration of specific three-fold coordinated oxygen vacancies and/or migration of positively charged hydrogen species, altering the relative intensity of the UV emissions that we observe via spatially resolved CL maps and linecuts.Together with the local electrical field maximum under reverse bias resulting from the fin/trench design, this local doping increase due to defect migration suggests a point-of-failure near the trench corners. More generally, defect migration and local doping changes under extreme electric fields in β-Ga_2O_3 demonstrates the potential impact of nanoscale device geometry in other high-power semiconductor device structures.

This work supported by AFOSR grant FA9550-18-1-0066 and NSF grant DMR-18-00130.This work also supported by AFOSR under Grant FA9550-18-1-0529 and made use of the Cornell Center for Materials Research Facilities supported by NSF MRSEC program (DMR-1719875).

Plenary Session
Room Jefferson 2-3 - Session PS2-WeM

Plenary Session II
Moderator: Dr. Kelson Chabak, Air Force Research Laboratory

8:45am **PS2-WeM-2 Plenary Lecture: Fundamental Limits of Ga_2O_3 Power Devices and How to Get There**, ***Huili Grace Xing,*** Cornell University**INVITED**

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