# Program Overview

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## 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.

[3] H. Shibata et al., Mater. Trans., vol. 48, no. 10, pp. 2782–2786, Oct. 2007.

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, "MEPhI", 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 $1 \times 10^{14}$-$2 \times 10^{16}$ 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 $2 \times 10^{16}$ Si/$cm^2$ (as-implanted and annealed at 1100 °C) were characterized with (scanning) transmission electron microscopy [(S)TEM].

For fluences of $1 \times 10^{15}$ 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.

1 Azarov, A. *et al., Phys. Rev. Lett.* **128**, 015704 (2022).

2 Anber, E. A. *et al., Appl. Phys. Lett.* **117**, 152101 (2020).

3 Kjeldby, S. B. *et al., J. Appl. Phys.* **131**, 125701 (2022).

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 °C, 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/$\mu m^2$ at -10 V) compared to S2-PD ($1.5 \times 10^{-4}$ nA/$\mu m^2$ 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.

## 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 ($\rho_c$) 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 $2.3x10^{-7}$ $\Omega.cm^2$, 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 $3.9x10^{-6}$ $\Omega.cm^2$, 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 $4.6x10^{-4}$ $\Omega.cm^2$. 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 $\rho_c$. 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 $cm^2/V{\cdot}s$. 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 $1.6x10^{-4}$ $\Omega/cm^2$. 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.

[1] S. J. Pearton et al., Appl. Phys. Rev., vol. 5, no. 1, p. 011301, Mar. 2018, doi: 10.1063/1.5006941. [2] M. J. Tadjer et al., J. Phys. D: Appl. Phys., vol. 54, no. 3, p. 034005, Oct. 2020, doi: 10.1088/1361-6463/abbc96.

**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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References

1. S. Hayashi, et al., ECS Trans., 16(8), 295 (2008).

2. S. Hayashi, et al., J. Electrochem. Soc., 155(2), H113 (2008).

3. J. Mc Kay, et al., ECS Trans., 64(5), 397 (2014).

**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 $cm^2/V{\cdot}s$ 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.

## 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, 600°C) 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 970°C 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 ~1.2e20$cm^{-3}$ 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 $cm^2/V{\cdot}s$ 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 °C in vacuum and up to 450 °C 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 °C. 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 °C in air [2]. The measured $I_D$-$V_D$ characteristics showed no current degradation up to 450 °C. At 500 °C, 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 °C because of contact degradation. The barrier height of $\phi_B$~ 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 $\phi_B$ 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 $\phi_B$ 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 °C 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 ($\mu_{FE}$) 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 $\mu_{FE}$ 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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# Author Index

## Bold page numbers indicate presenter