Advanced Characterization Techniques
Room Davis Hall 101 - Session AC+TM-MoM

Characterization/Modeling I

Moderators: Michael Scarpulla, University of Utah, **Uttam Singisetti**, University of Buffalo, SUNY

9:15am **AC+TM-MoM-4 Electric Field Induced Defect Redistribution at Ni-Ga_2O_3 Interfaces**, ***Daram Ramdin***, *H. Huang, S. Dhara, S. Rajan, J. Hwang, L. Brillson,* The Ohio State University

β-Ga_2O_3 is a prime semiconductor for high power electronics due to its high intrinsic critical field of ~ 8 MV/cm. However, premature dielectric breakdown that occurs at lower field gradients remains a challenge that is relatively unexplored at the atomic and nanoscale. Here we use UHV depth-resolved cathodoluminescence (DRCLS) correlated with scanning transmission electron microscopy (STEM) to describe how high electric fields in a Ni/Au Schottky diode on HVPE (001) Ga_2O_3 cause atomic lattice arrangements, depth-dependent phase changes, Ni diffusion and native defect rearrangements all on a nanometer scale and a function of increasing electric field gradient up to and past dielectric breakdown.

Before electrical fields are applied, DRCLS near the Ni/ β-Ga_2O_3 interfacial region exhibits new, above β-Ga_2O_3 band gap 5.29 eV and 5.82 eV CL emissions corresponding to a γ-Ga_2O_3 phase. Also present are a set of characteristic intrinsic β-Ga_2O_3 defect emissions including a ~2.4 eV feature which increases under the contact. STEM confirms a defective misaligned γ phase that is of average thickness ~ 5 nm.

With increasing reverse bias at 143 nm below the M-S interface, in-situ DRCLS shows increasing above-bandgap emissions relative to the intrinsic 3.2 eV and 3.6 eV emissions. Prior to breakdown, these ~5.2 eV and ~5.8 eV emissions remain without applied fields, indicating Ni diffusion and accompanying local phase inhomogeneities. After breakdown, these emissions are reduced, indicating reduced Ni and γ-Ga_2O_3 phase present at this depth. However, at the intimate interface, STEM imaging confirms that the defective layer thickness triples, with little Ni diffusion observed outside of the defective layer after breakdown.[1] These observations are consistent with Ni diffusion into β-Ga_2O_3 with metallization and subsequent reverse bias, then diffusion back towards the defective layer during the breakdown process, similar to the effect of annealing on this defective layer (unpublished). Breakdown experiments performed in air show that V_{Br} is 2.7x higher, indicating that thermal effects play a more pronounced role in the breakdown process in UHV. These results provide evidence that dielectric breakdown at the widely used Ni/ β-Ga_2O_3 contact involves an interplay of nanoscale phase change, Ni diffusion, and defect rearrangement.

Support acknowledged from AFOSR Grant No. FA9550-18-1-0066 (DNR & LJB) and AFOSR (GAME MURI) Grant No. FA9550-18-1-0479 (HLH,JH).

1. J. Shi et al., Appl. Mater. Int.2021, 13, 29083-29092.

9:30am **AC+TM-MoM-5 Charge State Transition Levels of Ni in *β*-Ga_2O_3 Crystals from Experiment and Theory: Eminently Suitable Candidate for Compensation**, ***Palvan Seyidov***, Leibniz-Institut für Kristallzüchtung, Germany*; J. Basile Varley,* Lawrence Livermore National Laboratory*; Z. Galazka, T. Chou, A. Popp, K. Irmscher, A. Fiedler,* Leibniz-Institut für Kristallzüchtung, Germany

β-Ga_2O_3 has emerged as a next-generation high-power application due to its large bandgap of 4.85eV and a high theoretical breakdown field of ~8MV/cm, which already resulted in established power rectifiers and MOSFETs with excellent characteristics.[1] Bulk single crystals for substrates can be grown with EFG[2] and Czochralski[3] methods. One of the critical criteria for achieving excellent characteristic in lateral devices is the choice of high-resistive free-standing substrates. In this respect, deep acceptor dopants are necessary to counter the unintentional donor impurities. Recently, Mg, Fe, and Co dopants have been proposed as potential deep acceptors for producing semi-insulating *β*-Ga_2O_3 crystals. However, if the acceptor level positions above the mid-band gap, it can lead to electron conduction and loss of the semi-insulating state at high fields or high temperatures, as is the case for Fe and Co dopants. On the other hand, the holes are not mobile (in VB) in *β*-Ga_2O_3 crystals resulting in a high semi-insulating state if the acceptor level positions below the mid-band gap, as is the case in the Mg acceptor dopant. However, the acceptor level of Mg positions only ~1.2eV above the VBM, where thermal ionization is to be expected at higher temperatures leading to loss of the semi-insulating state of substrates. Thus, an acceptor dopant is needed that has its acceptor level below and very close to the mid-band gap, which is the key factor for producing reliable semi-insulating *β*-Ga_2O_3 crystals.

We measured the photoconductivity, optical absorption, and temperature-dependent resistivity (up to 1100K) of Ni-doped *β*-Ga_2O_3 crystal grown by the Czochralski method[3]. Fitting results of photoconductivity measurement allow us to identify the energy of the E_{ZPL}, D_{FC},and hω of Ni-related deep levels. The first-principal calculations based on DFT support our identifications. Spectral regions observed in optical absorption mainly arise due to the charge transfer from Ni-related deep levels and CB or VB. High-temperature resistivity shows a thermal activation energy of ~2.0 eV. Conclusively, from the experiment and theory, a consistent energy scheme: an acceptor level of ~1.9 eV (above the VBM), and a donor level of ~3.8 eV (below the CBM) were identified. Due to the position of the acceptor level (below and close to the mid-band gap), Ni seems to be a promising acceptor dopant for producing semi-insulating *β*-Ga_2O_3 substrates for lateral power devices.

[1] A.J. Green et al., APL Mater **10**(2), 029201 (2022). [2] A. Kuramata et al., Jpn. J. Appl. Phys. **55**(100), 1202A2 (2016). [3]Z. Galazka; J. Appl. Phys. 131 (2022) 031103.

9:45am **AC+TM-MoM-6 Comparative Study of Temperature-Dependent Bandgap Transitions in Ga_2O_3 Polymorphs**, ***Benjamin M. Janzen***, *N. Hajizadeh, M. Meißner, M. Marggraf, C. Hartung,* Technical University of Berlin, Germany*; Z. Galazka,* Leibniz-Institut für Kristallzüchtung, Berlin, Germany*; P. Mazzolini, A. Sacchi, R. Fornari,* Department of Mathematical, Physical and Computer Sciences, University of Parma, Italy*; C. Petersen, H. von Wenckstern, M. Grundmann,* Universität Leipzig, Felix-Bloch-Institut für Festkörperphysik, Germany*; E. Kluth, M. Feneberg, R. Goldhahn,* Otto-von-Guericke-University Magdeburg, Germany*; T. Oshima,* Department of Electrical and Electronic Engineering, Saga University, Japan*; T. Kato, H. Nishinaka,* Faculty of Electrical Engineering and Electronics, Kyoto Institute of Technology, Japan*; J. Varley,* Lawrence Livermore National Laboratory*; M. Wagner,* Paul-Drude-Institut für Festkörperelektronik, Germany

The temperature dependence of the optical bandgap has rarely been investigated experimentally for the different polymorphs of Ga_2O_3. A direct comparison of the temperature dependence as well as the electron-phonon coupling strengths is made considerably more difficult by the different experimental methods (e.g., reflection spectroscopy, absorption spectroscopy or ellipsometry) used to study the various polymorphs. In particular, there is no study in the literature that provides a self-consistent comparison between the band gap values and the electron-phonon coupling strengths of the different polymorphs using the same experimental technique.

We provide a combined experimental-theoretical study to investigate the electronic bandgap transitions in monoclinic [1] β-, orthorhombic rotational-domain [2] as well as single-domain[3] κ-, rhombohedral [4] α-, defective spinel [5] γ- and cubic bixbyite [6] δ-Ga_2O_3as a function of the sample temperature. Temperature-dependent UV photoluminescence excitation (PLE) spectroscopy is employed in the temperature range between 5 K and 300 K and the obtained bandgap energies are compared with room temperature measurements of the dielectric function as determined by spectroscopic ellipsometry. The temperature dependencies are discussed in conjunction with DFT calculations regarding the effects of electron-phonon coupling and the averaged phonon energies.

At 5K, we find that γ and α possess the largest bandgap energy values around 5.36 eV, with the monoclinic β-polymorph's observed polarization-dependent direct band-to-band transitions exhibiting the smallest bandgap energies between 4.72 eV and 4.99 eV. Regarding the strength of the electron-phonon coupling, we observe the strongest coupling for γ or weakest coupling for κ and δ, whereas the interaction appears similarly intense for α with respect to β. In contrast to the rotational domain structured κ-Ga_2O_3 thin film, the single-domain film reveals a directional dependence of the energy bandgap when polarizing the incident light along the crystallographic a- or b-directions, respectively.

[1]: Z. Galazka, Semicond. Sci. Technol., 33(11), 113001 (2018).

[2]: P. Mazzolini, B. M. Janzen et al., Adv. Funct. Mater., 33(2), 2207821 (2023).

[3] H. Nishinaka et al., *Jpn. J. Appl. Phys.,* 61(1), 018002 (2022).

[4]: S. Vogt et al., Phys. Status Solidi A, 220(3), 2200721 (2023).

[5]: L. E. Ratcliff, B. M. Janzen et al., Adv. Mater., 34(37), 2204217 (2022).

[6]: T. Kato et al., ACS Appl. Electron. Mater., 5(3), 1715 (2023).

10:00am **AC+TM-MoM-7 Strain and Composition Dependencies in $(Al_xGa_{1-x})_2O_3$ Alloys**, ***Rafal Korlacki***, *J. Knudtson, M. Stokey, M. Hilfiker,* University of Nebraska-Lincoln*; V. Darakchieva,* Lund University, Sweden*; M. Schubert,* University of Nebraska-Lincoln

Strain caused by the lattice mismatch in heteroepitaxial thin-films can be used to optimize the optical performance, as it has been demonstrated for the ternary system of (Al,Ga)N.[1-2] In order to apply the same principle to $(Al_xGa_{1-x})_2O_3$ alloys, the details of the strain relationships for various electronic and optical properties as a function of composition are needed. We use symmetry-based analysis on how the energy eigenvalues and other properties depend on the components of stress and strain tensors.[3] Then, we perform density functional theory (DFT) calculations for a representative set of structures realizing different model deformation scenarios for both, Ga_2O_3 and Al_2O_3, in monoclinic and rhombohedral phases. We obtain the linear deformation potentials for energy eigenvalues [3,4] and other material properties that can be extracted from first principles calculations, such as band-to-band transitions, effective mid-band energies, refractive indices, components of the dielectric tensors, and effective mass parameters. Then, Vegard's rule allows us to construct a simple universal model of strain and composition dependencies of these properties in heterostructures under specific strain patterns,[5,6] and thus allowing rational strain engineering to aid design of new $(Al_xGa_{1-x})_2O_3$-based electronic and photonic devices.

[1] D. Li, K. Jiang, X. Sun, and C. Guo, *Adv. Opt. Photon.***10**, 43-110 (2018)

[2] J.-M. Wagner and F. Bechstedt, *Phys. Rev. B***66**, 115202 (2002)

[3] R. Korlacki, M. Stokey, A. Mock, S. Knight, A. Papamichail, V. Darakchieva, and M. Schubert, *Phys. Rev. B***102**, 180101(R) (2020)

[4] R. Korlacki, J. Knudtson, M. Stokey, M. Hilfiker, V. Darakchieva, and M. Schubert, *Appl. Phys. Lett.***120**, 042103 (2022)

[5] R. Korlacki, M. Hilfiker, J. Knudtson, M. Stokey, U. Kilic, A. Mauze, Y. Zhang, J. Speck, V. Darakchieva, and M. Schubert¸ *Phys. Rev. Appl.***18**, 064019 (2022)

[6] M. Stokey, R. Korlacki, J. Knudtson, A. Mock, M. Hilfiker, A. Mauze, Y. Zhang, J. Speck, A. Papamichail, S. Knight, V. Darakchieva, and M. Schubert, "Phonon modes and strain effects in β-$(Al_xGa_{1-x})_2O_3$," in preparation

10:15am **AC+TM-MoM-8 10 kV Ga_2O_3 Schottky Rectifier Operational at 200 ℃**, ***Yuan Qin***, *M. Xiao, M. Potter, Y. Ma,* Center of Power Electronics Systems, Virginia Polytechnic Institute and State University*; J. Spencer,* Naval Research Laboratory*; Z. Du,* Ming Hsieh Department of Electrical Engineering, University of Southern California*; A. Jacobs,* Naval Research Laboratory*; K. Sasaki,* Novel Crystal Technology Inc., Japan*; H. Wang,* Ming Hsieh Department of Electrical Engineering, University of Southern California*; M. Tadjer,* Naval Research Laboratory*; Y. Zhang,* Center of Power Electronics Systems, Virginia Polytechnic Institute and State University

This work demonstrates a novel lateral Ga_2O_3 Schottky barrier diode (SBD) with a *BV* over 10kV and a thermally-stable 10kV blocking at high temperatures up to 200°C. The device design to enable such performance is a NiO-based reduced-surface-field (RESURF) structure that achieves a charge balance with the Ga_2O_3 channel at high reverse bias.

Fig. 1(a)and(b)show the schematic and top-view scanning electron microscopy (SEM) image of the RESURF Ga_2O_3 SBD, respectively. A gap between the p-NiO layer and cathode (L_{pc}) is designed to prevent the possible leakage current and punch-through in NiO.

Fig. 1(c) shows the depth profile of the net donor concentration in the Ga_2O_3 epi layer. A total charge density (σ_n) of $3.8\times10^{12}cm^{-2}$ is estimated in n-Ga_2O_3. A NiO/n^+-Ga_2O_3 p-n diode is fabricated to extract the acceptor concentration in NiO, which is revealed to be $8\times10^{17}cm^{-3}$ at 25°C and shows little changeat 200°C (Fig. 1(d)). If a charge imbalance margin below 15% is kept for practical device fabrication, the NiO thickness (t_{NiO}) range is estimated to be 61-82 and 58-78nm for the anode-to-cathode length (L_{AC}) of 30 and 50µm.

Fig. 2(a)-(c) show the simulated electric field (E-field) contours of RESURF SBDs with different t_{NiO}. In charge balance condition (t_{NiO}=75nm), the E-field are more evenly distributed in Ga_2O_3 channel. Fig. 2(d) manifests that the NiO RESURF region could increase the device on-resistance (R_{on}) due to the vertical depletion effect.

Fig. 3(a) and (b) show the reverse I-V characteristics of the Ga_2O_3 RESURF SBDs with various t_{NiO} for L_{AC} of 30 and 50µm. The breakdown voltage (*BV*) increases with the increasing t_{NiO}, reaching>10kV (the measurement limit of our test setup) at t_{NiO}=75nm, and starts to decrease at larger t_{NiO}. The two sets of devices can be swept repeatedly up to 10kV at 200°C (Fig. 3(c)).Fig. 3(d)suggeststhe determining impact of charge balance on the *BV*.

Fig. 4(a) shows the forward I-V characteristics of the non-RESURF and 75-nm-RESURF SBDs, both with L_{AC} =30 and 50µm. The larger R_{on} of RESURF SBDs can be explained by the simulation results in Fig. 2(d).The specific R_{on} of the RESURF SBDs with L_{AC}=30µm is calculated to be $0.27\Omega\cdot cm^2$. Fig. 4(b) shows the temperature-dependent forward I-V characteristics of this RESURF SBD.

Fig. 5 benchmarks the $R_{on,sp}$ versus *BV* as well as the *BV* versus maximum operational temperature for our devices and the state-of-the-art Ga_2O_3 devices. Our device shows the highest *BV* and the operational temperature in multi-kilovolt Ga_2O_3 devices.

Epitaxial Growth
Room Davis Hall 101 - Session EG-MoM
Bulk/Epitaxial I

Moderator: Hongping Zhao, Ohio State University

10:45am **EG-MoM-10 Advances in the MOCVD Growth of β-Ga_2O_3 and Related Heterostructures**, ***Andrei Osinsky***, Agnitron Technonolgy, Inc.*; F. Alema,* Agnitron Technology, Inc. **INVITED**

β-Ga_2O_3 has attracted extensive interest in power electronic applications owing to its large bandgap of ~ 4.9 eV, estimated high breakdown field of ~ 8 MV/cm, and availability of melt grown high quality β-Ga_2O_3 substrates. The growth of high-quality epitaxial films with low dislocation density and background impurity is critical to realize the projected device performances. Available epitaxial methods to grow β-Ga_2O_3 thin films include MBE, HVPE, and MOCVD. But, despite coming late to the field, the MOCVD method has proven to be suitable for producing high-quality epitaxial β-Ga_2O_3 films at a fast growth rate with uniform and controllable doping [1]. The highest purity β-Ga_2O_3 films have been reported from MOCVD with record low-temperature electron mobility exceeding 23,000 cm^2/Vs and low~10^{13} cm^{-3} compensating acceptors [2]. Also, a recent record-breaking result for lateral Ga_2O_3 MESFETs with a lateral figure of merit (LFOM) of 355 MW/cm^2 and a breakdown voltage of ~2.5 kV [3], and a record low specific contact resistance ~10^{-7} Ωcm^2[4] were reported based on MOCVD grown epitaxial Ga_2O_3 films.

This presentation will discuss recent progress in the growth of high-quality β-Ga_2O_3 thin films and related materials using MOCVD. The use of Ga precursors, including triethylgallium (TEGa) and trimethylgallium (TMGa), for the growth of Ga_2O_3 will be presented. Their advantages and disadvantages in realizing high-purity, carbon-free, epitaxial Ga_2O_3 films will be discussed. Critical process conditions and MOCVD reactor geometries on achieving high purity β-Ga_2O_3 films with high electron mobility and low background carrier concentration, including doping control in this range, will be discussed. This paper will also discuss the MOCVD growth of high Al composition (up to 30%) high quality strained β-$(AlGa)_2O_3$/Ga_2O_3 heterostructures and superlattices on various orientations of β-Ga_2O_3 substrates. The MOCVD growth of heavily doped (>10^{20} $1/cm^3$), highly conductive β-Ga_2O_3, andstrained β-$(Al_xGa_{1-x})_2O_3$/β-Ga_2O_3 heterostructures will be presented. We will also present the demonstration of record low resistance Ohmic contacts on heavily Si doped epitaxial β-Ga_2O_3 and strained β-$(Al_xGa_{1-x})_2O_3$ epilayers with varying Al composition. A recent in-situ non-destructive etching of Ga_2O_3 in MOCVD followed by a regrowth process will also be discussed.

[1] F. Alema *et al.*, Journal of Crystal Growth 475 (2017) 77-82.

[2] G. Seryogin *et al.,* Applied Physics Letters 117 (2020) 262101.

[3] A. Bhattacharyya *et al.*, IEEE Electron Device Letters 42 (2021) 1272-1275.

[4] F. Alema *et al.,* EEE Electron Device Letters 43 (2022) 1649-1652.

11:15am **EG-MoM-12 MOVPE of (100) β-Ga2O3 for Vertical Power Devices - Challenges to Epitaxial Growth Process**, ***Andreas Popp***, *T. Chou, S. Bin Anooz, R. Grüneberg, V. Thuy, J. Rehm, A. Akhtar, Z. Galazka, P. Seyidov, K. Irmscher,* LEIBNIZ-INSTITUT FÜR KRISTALLZÜCHTUNG im Forschungsverbund Berlin e.V, Germany*; M. Albrecht,* LEIBNIZ-INSTITUT FÜR KRISTALLZÜCHTUNG im Forschungsverbund Berlin e., Germany*; A. Fiedler,* LEIBNIZ-INSTITUT FÜR KRISTALLZÜCHTUNG im Forschungsverbund Berlin e.V, Germany

Beta-gallium oxide (β-Ga_2O_3) is a promising ultra-wide bandgap (~ 4.8 eV) semiconductor material for the application field of power electronic

converters. The theoretical breakdown field strength of up to 8 MV/cm[1] can be best exploited using a vertical architecture for β-Ga_2O_3 based transistors.A high-quality homoepitaxial drift layer plays a crucial role in such a vertical device structure. Here, we report our developed process via metal-organic vapor phase epitaxy (MOVPE) to overcome the main issue associated with the homoepitaxial drift layer: (a) low doping (10^{16} cm^{-3} range) concentrations, (b) layer thicknesses of several µm while maintaining a low density of structural and point defects and (c) high growth rates (µm/h).

A high growth rate process of up to 1.5 µm/h was achieved for Si-doped (100) β-Ga_2O_3 homoepitaxial films grown via MOVPE on Czochralski-grown semi-insulating[2,3] and conductive[4] (100) 4° off β-Ga_2O_3 substrates while maintaining the step-flow growth mode up to a film thickness of 4 µm[5]. The enhanced diffusion channel due to forming a Ga adlayer was proposed as the possible growth mechanism[6]. Furthermore, we also report the formation of parasitic particles as a killer issue during the growth, which can be suppressed by a close showerhead to substrate gap and a high total gas flow[7]. With our optimized process, Si doping enabled precise control of the n-type conductivity of the layers with free electron concentrations ranging from 5×10^{16} $cm^{-3}$to 1.5×10^{19} $cm^{-3,}$ and corresponding mobilities from 163 $cm^2 \cdot V^{-1} \cdot s^{-1}$ to 21 $cm^2 \cdot V^{-1} \cdot s^{-1}$ were measured by room temperature Hall measuerements. Temperature-dependent Hall measurements let expect a low background compensating acceptor concentration of 4 x $10^{15}cm^{-3}$, indicating a doping level down to mid $10^{15}cm^{-3}$ is still possible.

[1]M. Higashiwaki et al., *Semicond. Sci. Technol.* **2016**, *31*, 34001.

[2]Z. Galazka et al., *Prog. Cryst. Growth Charact. Mater.* **2021**, *67*, 100511.

[3]P. Seyidov et al., *APL Materials* **2022**, *10, 111109* (2022)

[4]Z. Galazka et al., *Appl. Phys. Lett.* **2022**, *120*, 152101.

[5]T.-S. Chou et al., *Jpn. J. Appl. Phys.* **2023**, *62*, SF1004.

[6]T.-S. Chou et al., *AIP Adv.* **2021**, *11*, 115323.

[7]T.-S. Chou et al., *Appl. Phys. Lett.* **2023**, *122*, 052102.

11:30am **EG-MoM-13 MOCVD Epitaxy of (010) β-Ga_2O_3 with Fast Growth Rate and the Role of Carbon in Charge Compensation**, ***Lingyu Meng***, *A. Bhuiyan, D. Yu, H. Zhao,* The Ohio State University

β-Ga_2O_3 has emerged as a promising semiconductor candidate for future power electronic and radio frequency device applications, because of its ultra-wide bandgap (4.8 eV) and high critical field strength (8 MV/cm). Previously, metalorganic chemical vapor deposition (MOCVD) of β-Ga_2O_3 using triethylgallium (TEGa) as the Ga precursor has been demonstrated with record electron mobilities approaching the theoretical values. The use of trimethylgallium (TMGa) as the Ga precursor with higher vapor pressure enables the MOCVD growth of β-Ga_2O_3 with much faster growth rates (> 3µm/hr) for thick film growth.

In this work, a systematic study of the MOCVD growth of (010) β-Ga_2O_3 using TMGa was performed. Both TMGa molar flow rate and growth temperature play an important role on the β-Ga_2O_3 MOCVD growth rate. With a TMGa molar flow rate of 116 µmol/hr, β-Ga_2O_3 fast growth rate of 6.7 µm/hr was achieved at 950°C. The surface morphologies of the MOCVD β-Ga_2O_3 films were highly dependent on the growth conditions, particularly chamber pressure. For films grown at a growth rate of ~3 µm/hr, record room temperature electron Hall mobilities ranging between 190 cm^2/Vs and 93 cm^2/Vs were achieved with carrier concentrations between 1.6×10^{16} and 3.8×10^{19} cm^{-3}. Temperature-dependent charge transport characteristics revealed a low charge compensation level (~1.5×10^{16} cm^{-3}) and a decent low-temperature peak electron mobility (3425 cm^2/Vs at 53K).

The impurities incorporation in the MOCVD grown (010) β-Ga_2O_3 thin films with different growth rates was probed by the quantitative secondary-ion mass spectroscopy (SIMS). SIMS results revealed that both [C] and [H] increase as the TMGa molar flow rate/growth rate increases. However, [C] increases at a much faster rate as compared to [H]. By comparing the electron Hall measurement results and the quantitative SIMS characterization, the net impurity concentration ([C]-[H]) matches well with the compensation level in the MOCVD β-Ga_2O_3 grown at the different growth rates. Therefore, the incorporated H forms neutral C-H complexes and thus passivates the compensation effect from pure C. This mechanism has been proposed from theoretical study based on the DFT calculations.

In summary, MOCVD growth of (010) β-Ga_2O_3 using TMGa as the Ga precursor was systematically studied. The role of C compensation and passivation from C-H complexes in the MOCVD grown films were proposed based on the experimental evidence.

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11:45am **EG-MoM-14 Controllable Deep Acceptor Doping in MOCVD β-Ga_2O_3 to Compensate Parasitic Interface Charges**, ***Fikadu Alema***, Agnitron Technology; *T. Itoh,* Materials Department, University of California, Santa Barbara; *W. Brand, A. Osinsky,* Agnitron Technology; *J. Speck,* Materials Department, University of California, Santa Barbara

One of the challenges in developing β-Ga_2O_3 lateral devices is the presence of parasitic charges at the epilayer-substrate interface due to the Si impurity that accumulates at the interface. One method that has been proposed recently to manage the interface Si is to etch the β-Ga_2O_3 substrate in hydrofluoric acid (HF) for an extended time before the growth of the films [1]. This method does not eliminate the Si at the interface but reduces its concentration just below the concentration of Fe in the substrate, leading to partial compensation. The other method to manage the interface Si is to compensate with deep acceptor dopants, such Mg, Fe, and N, among which N is less affected by thermal diffusion, making it a dopant of choice [2].

In this work, we report on controllable doping of N into Ga_2O_3 using nitrous oxide (N_2O) and ammonia diluted in nitrogen (NH_3/N_2) as sources for N. The incorporation efficiency, reproducibility, and controllability of N doping into Ga_2O_3 films will be discussed as a function of process conditions for both sources. Incorporating N into Ga_2O_3 is found to be sensitive to process conditions when N_2O is used as a source. A maximum N concentration of ~2×1019 cm-3 was achieved by growing the layer at a low substrate temperature. However, using NH_3/N_2, the doping of N into Ga_2O_3 is controllable through the molar flow rate. With the increase in the NH_3/N_2 molar flow rate from $\sim 1.8 \times 10^{-8}$ mol/min to 1.45×10^{-6} mol/min, the N impurities incorporated into the β-Ga_2O_3 layers increased from $\sim 1 \times 10^{18}$ cm^{-3} to $\sim 2 \times 10^{20}$ cm^{-3}. For both sources, hydrogen was found to incorporate into the films along with N, but annealing at reduced pressure helps to drive out the hydrogen from the film. For the NH_3/N_2 source, growing the layers at elevated temperatures (>900 C) also effectively reduced H incorporation into the film by as much as ~10× with no effect on the incorporation of N. This paper will also discuss the impact of exposing the surface of Ga_2O_3 substrate to NH_3/N_2 and halide based precursors to manage the interface Si.

[1] A. Bhattacharyya etal. C APL Materials 11, 021110 (2023).

[2] M.H. Wong et.al. Applied Physics Letters 113 , 102103 (2018).

12:00pm **EG-MoM-15 Si Accumulation on Ga_2O_3 Surfaces**, ***Jon McCandless***, *C. Gorsak, V. Protasenko, D. Schlom, M. Thompson, H. Xing, H. Nair, D. Jena,* Cornell University

In 2022, we demonstrated a high degree of doping control ($1x10^{17}$ to $1x10^{20}/cm^3$) in *β*-Ga_2O_3 films grown by molecular beam epitaxy with mobilities of ~130 cm^2/Vs in the lowest doped samples.[1] However, we discovered some samples where, despite being grown under the same conditions, the mobility would be ~1 cm^2/Vs. To understand a potential impurity related origin of these low mobilities, secondary ion mass spectrometry (SIMS) was performed. Over 8 samples, we observed significant Fe variation within the substrate and significant Si variation at the surface. Depending on the substrate, the surface Si may or may not have been fully compensated by the Fe. In the worst case, a high-density of uncompensated free carriers exist at the interface with a low mobility which in turn affects the Hall effect measurement. Moreover, this same uncompensated charge can prevent confinement, or create a parallel conducting path for 2D electron gasses, thereby hindering the performance of high electron mobility transistors.[2]

The Si contamination is thought to arise from the polishing process and/or from siloxanes adsorbed from the air, and which are particularly difficult to remove.[3]

To quantify and study the Si accumulation and possible removal strategies, we investigated how Si accumulates on the film surface when exposed to air. We grew UID layers by molecular beam epitaxy, removed the sample and exposed it to air for different amounts of time. After less than 20 minutes of exposure to air, the accumulated Si on a clean surface had a sheet density (n_s) of ~$2x10^{12}/cm^2$. The n_s continued to increase with longer exposure times in air, saturating at ~ $7x10^{12}/cm^2$ after an 8-hour exposure. Next, etching studies were performed to investigate possible removal of the SiO_x on the surface. *β*-Ga_2O_3 films were grown by metal-organic chemical vapor deposition and the surface was exposed to air for 2 hours to allow for the accumulation of Si. The surface was then etched in HF (49%) for varying

times to remove the accumulated Si. After etching for 15 minutes, the Si sheet charge was reduced by ~1 order of magnitude to~ $3x10^{11}/cm^2$.

Lastly, simulations were carried out to investigate compensation doping. Under the worst case, (i.e. low Fe density within the substrate and high Si density at the interface), the required compensation would have to be > $10^{20}/cm^3$, but at this Fe density the film quality degrades. Therefore, we believe the optimal solution requires HF etching along with compensation doping.

1. APL, 121, 072108 (2022); 2. APEX, 10, 071101 (2017); 3. Chemosphere,92, 905-910 (2013)

Keynote Address
Room Davis Hall 101 - Session KEY-MoM

Keynote Address I

Moderators: Michael Scarpulla, University of Utah, **Uttam Singisetti**, University of Buffalo, SUNY

8:30am **KEY-MoM-1 Welcome and Opening Remarks**,

8:45am **KEY-MoM-2 Gallium Oxide as a Material for Power Device Applications**, ***Akito Kuramata***, Novel Crystal Technology, Inc., Japan **INVITED**

Ga_2O_3 is expected as a material for next generation power devices. Since it has a large bandgap energy and a large breakdown electric field strength, it is suitable for high breakdown voltage applications. It is a material that can be produced at a lower cost than SiC and GaN because it can be melt-grown and its hardness is not high.

Currently, 100-mm substrates manufactured by the EFG method are commercially available. A 100-mm epitaxial wafer with a carrier concentration of 10^{15}-10^{17} cm^{-3}, grown by the HVPE method, has also been commercialized. There are no commercial Ga_2O_3 devices yet, but research is progressing. So far, SBDs and FETs have been demonstrated with ampere-class currents and breakdown voltages of 1 kV or higher. In the presentation, I will introduce the above and talk about the challenges for commercialization of Ga_2O_3 devices.

Advanced Characterization Techniques
Room Davis Hall 101 - Session AC+DI+HM+TM-MoA
Characterization/Modeling II

Moderator: Mike Thompson, Cornell University

3:45pm **AC+DI+HM+TM-MoA-9 The Physics of Low Symmetry Semiconductors: Gallium Oxide for the Future of Green Energy as Example**, ***Mathias Schubert***, *R. Korlacki, M. Stokey, M. Hilfiker,* University of Nebraska-Lincoln, USA*; S. Knight,* Linkoping University, Sweden*; S. Richter,* Lund University, Sweden*; A. Ruder,* University of Nebraska-Lincoln, USA*; A. Papamichael, V. Stanishev,* Linkoping University, Sweden*; J. Speck,* University of California Santa Barbara*; V. Darakchieva,* Lund University, Sweden **INVITED**

The physics of GaAs (zincblende structure) and Gallium nitride (wurtzite structure) led to disruptive technologies driven by extreme properties such as small effective mass, large direct bandgap, and piezoelectric polarization. Gallium reappears in a monoclinic-structure oxide with enormous prospects for applications in power electronics for the future of green energy. Numerous new phenomena hitherto unknown for traditional semiconductors occur in monoclinic symmetry semiconductors such as non-parallel phonon-plasmon scattering, hyperbolic shear polaritons, splitting of associated transverse and longitudinal phonon modes, non-degenerate highly anisotropic fundamental excitonic band-to-band transitions, direction-dependent band alignments, and complex defect spin interactions within the highly anisotropic host lattice. The influences of composition, strain, doping, and defects are discussed for Ga2O3 and related alloys, and special emphasis is paid to new semiconductor phenomena, and consequences for thin film growth and device designs are pointed out. Methods such as generalized ellipsometry, the optical Hall effect, Terahertz electron paramagnetic resonance ellipsometry, and density functional theory computations are employed for characterization and analysis.

4:15pm **AC+DI+HM+TM-MoA-11 Investigation of Split Vacancy and Interstitial Defects and Ionic Diffusion Mechanisms in β-Ga_2O_3: A Direct Approach via Master Diffusion Equations**, ***Channyung Lee***, *E. Ertekin,* University of Illinois Urbana-Champaign

The low symmetry of the monoclinic structure of β-Ga_2O_3 has led to interesting discoveries of a variety of complex configurations of intrinsic defects, such as Ga vacancies split into two or three different Ga sites. These complex defects contribute to the fast, yet highly anisotropic, diffusion of β-Ga_2O_3, making it challenging to understand the dominant diffusion mechanisms of Ga cations. While previous computational studies have analyzed some migration pathways between these complex split defects, a comprehensive understanding of the overall diffusion mechanism, and predictions of the components of the full diffusivity tensor accounting for the full spectrum of intrinsic defects is not yet achieved. In this work, we aim to calculate from the first principles the 3D diffusion tensors for Ga interstitial and vacancy self-diffusion via the direct approach of solving the master diffusion equations. To achieve this, we first explore the maximum extent of "N"-split defects with large configurational complexity, including their formation energies. With the dominant low-energy defects identified, we then construct the complete diffusion network taking into account all stable split defects and all possible hops connecting them (including the interstitialcy mechanism). The nudged elastic band method is next used to accurately determine the hopping barriers, and the barriers and diffusion pathways are used to construct the complete master diffusion equations for Ga cations. Finally, the solution to these equations yields the Onsager transport coefficients, resulting in the 3d diffusion tensors and identification of the most active diffusion paths along three different crystallographic directions. Our analysis includes the identification of over 50 unique interstitial and interstitialcy hops between 20 different configurations of Ga interstitials and more than 30 unique vacancy hops between 15 different configurations of Ga vacancies. Extended N-split Ga defects are remarkably more stable than simple point defects, and play a critical role in creating low-energy pathways for both interstitial and vacancy diffusion. Furthermore, we found that selecting the appropriate supercell size is crucial for accurately describing the formation energies of N-split defects and calculating their associated migration energy barriers. Our study provides a clear understanding of the migration mechanisms of native Ga species in β-$Ga_2O_3$and the origin of its anisotropic diffusion, which can contribute to further developments in the design and optimization of β-Ga_2O_3-based electronics.

4:30pm **AC+DI+HM+TM-MoA-12 Hybrid Metal/low-k/$BaTiO_3$/*β*-Ga_2O_3 Metal-Insulator-Semiconductor Junctions Enable Electric Field of 6.8 MV/cm**, ***Ashok Dheenan***, *S. Dhara,* Ohio State University*; A. Islam, A. Green,* Air Force Research Laboratory*; S. Rajan,* Ohio State University

β-Ga_2O_3 is an ultrawide bandgap semiconductor that has attracted interest for use in high-power electronics due to its theoretical breakdown field of 8 MV/cm and availability of native bulk substrates. Integration of high-quality insulator layers is critical to realizing the material breakdown fields of *β*-Ga_2O_3 devices. Recent work has demonstrated the advantages in using hybrid extreme-k/low-k insulator stacks to enable high average electric fields in the *β*-Ga_2O_3 [N.K. Kalarickal *et* al. *IEEE EDL* (2021)]. In this work, we study such hybrid insulator stacks. Four different insulator stacks were used to fabricate metal-oxide-semiconductor capacitors (MOSCAPs) on top of (010) *β*-Ga_2O_3 Sn-doped substrates. The first set of samples consisted of a 20 nm Al_2O_3 low-k layer and $BaTiO_3$ (BTO) layers of 20 and 35 nm, respectively. The second two samples used 24 nm of SiO_2 with BTO layers of 35 nm and 50 nm, respectively. Al_2O_3 and SiO_2 were deposited by plasma-assisted atomic layer deposition after a Piranha/HF clean [A.E. Islam *et* al. *IEEE TED* (2022)]. BTO layers were deposited by RF sputtering. All thicknesses were confirmed by ellipsometry of coloaded Si. The backside and top contacts were deposited by e-beam evaporation to complete fabrication. The samples were analyzed in terms of breakdown strength, C-V characteristics and supported reverse field in the Ga_2O_3. The sample with 50 nm of BTO on 24 nm SiO_2 resulted in a larger oxide capacitance, likely due to the increased permittivity of the BTO due to higher thermal budget. For breakdown measurements, a leakage current of 1 mA/cm^2 was defined as the breakdown limit for all devices. The field in the Ga_2O_3 was calculated by extracting the effective donor density from C-V and under the assumption of no charge in the dielectric layers. The sample with 20 nm Al_2O_3 and 20 nm BTO showed the best performance, with a forward breakdown electric field of 5.7 MV/cm in the Al_2O_3 and reverse breakdown field of 6.8 MV/cm *in the β-Ga_2O_3*. This is one of the highest reverse breakdown fields reported to date for Gallium Oxide in such a junction and shows the potential of hybrid low-k/high-k stacks to enable extreme fields in ultra-wide bandgap semiconductors. In summary, we have studied the properties of hybrid low-k/high-k insulator stacks on *β*-Ga_2O_3 and shown that such stacks can enable excellent reverse breakdown fields in *β*-Ga_2O_3 power devices. We acknowledge funding from Department of Energy / National Nuclear Security Administration under Award Number(s) DE-NA0003921, and AFOSR GAME MURI (Award No. FA9550-18-1-0479, project manager Dr. Ali Sayir).

4:45pm **AC+DI+HM+TM-MoA-13 Towards Controlled Transfer of (001) β-Ga_2O_3 to (0001) 4H-SiC Substrates**, ***Michael Liao***, National Research Council Postdoctoral Fellow at the U.S. Naval Research Laboratory*; K. Huynh,* University of California Los Angeles*; J. Lundh,* National Research Council Postdoctoral Fellow at the U.S. Naval Research Laboratory*; M. Tadjer, K. Hobart,* U.S. Naval Research Laboratory*; M. Goorsky,* University of California Los Angeles

We demonstrate successful blistering of He-implanted (001) β-Ga_2O_3, bonding to (0001) 4H-SiC, and initial results towards large-area transfer of (001) β-Ga_2O_3 to SiC. Compatible with large-scale processing, exfoliation is an important step in controlled-thickness transfer of films for heterogeneous integration. Furthermore, integration of β-Ga_2O_3 to high thermal conductivity materials will be crucial for thermal management of high-power devices. Two-inch (001) β-Ga_2O_3 wafers were implanted with He^+ at an energy of 160 keV and a dose of 5×10^{16} cm^{-2}, mimicking our previous parameters used to successfully exfoliate (010) β-Ga_2O_3.[1] Strain fringes were observed after the implant which corresponded to a maximum strain of ~1.7%, which is higher than the ~1% strain when implanting (010) β-Ga2O3[1] likely due to the larger Poisson's ratio of (001) β-Ga_2O_3.[2] The implanted substrates were then bonded to (0001) SiC at room temperature using a ~5 nm Ti interlayer to assist with the bond. Both unbonded implanted substrates and the bonded structures were first annealed at 200 °C for 10 hours to simultaneously initiate He bubble nucleation at the projected range (~0.68 µm) and strengthen the bond. Then, even after annealing at 500 °C for 10 hours to initiate bubble growth, the (001) β-Ga_2O_3 did not transfer to the (0001) 4H-SiC. Unlike what was observed for (010) β-Ga_2O_3,[1] blistering did not even occur at this temperature. Annealing at 800 °C for up to 12 hours resulted in ~10 µm blisters for the unbonded substrates, which is typically an indication that large wafer-area transfer can be achieved if bonding was done prior to annealing.[3] However, the β-Ga_2O_3 substrate did not wafer split from the bonded structure, and instead only small area transfers up to ~200 µm were achieved. Only ~7% of the total bonded area transferred while the entire structure remained bonded.

Strategies to improve transfer will be presented, including initiating a cold split prior to exfoliation and refined annealing strategies to improve He bubble nucleation and larger bubble growth at the projected range. These are promising results towards achieving large wafer-scale (001) β-Ga_2O_3 composite wafers, and when combined with subsurface damage-free chemical mechanical polishing,[4] these composite wafers would be suitable for subsequent devices and/or epitaxial growth.

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2. K.Adachi,et al., J.Appl.Phys., 124 085102 (2018)

3. M.Bruel,et al., Jpn.J.Appl.Phys., 36 1636 (1997)

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Electronic and Photonic Devices, Circuits and Applications
Room Davis Hall 101 - Session EP+HM+MD-MoA

Processes/Devices I

Moderator: Yuhao Zhang, Virginia Tech

1:45pm **EP+HM+MD-MoA-1 Gallium Oxide – Heterogenous Integration with Diamond for Advanced Device Structures**, *H. Kim, A. Bhat, A. Nandi, V. Charan, I. Sanyal, A. Mishra, Z. Abdallah, M. Smith, J. Pomeroy, D. Cherns,* ***Martin Kuball,*** University of Bristol, UK **INVITED**

Potentials for heterogenous integration of Ga_2O_3 with high thermal conductivity materials such as diamond for enabling energy-efficient kV-class power devices are being discussed. The integration alleviates Ga_2O_3 material drawbacks such as its low thermal conductivity and inefficient hole conductivity. The benefits of heterogeneous integration are for example demonstrated through electrical and thermal simulations of a Ga_2O_3-Al_2O_3-diamond superjunction based Schottky barrier diode. The simulation studies show that the novel device has potential to break the R_{ON}-breakdown voltage limit of Ga_2O_3, while showing relatively low rise in temperature compared to conventional devices. As step into their realization, experimental Al_2O_3 assessment namely ledge features in the capacitance-voltage (CV) profiles of Ga_2O_3 metal-oxide-semiconductor (MOS) capacitors were investigated using UV-assisted CV measurements; an interface trapping model is presented whereby the capacitance ledge is associated with carrier trapping in deep-level states at the Al_2O_3/Ga_2O_3 interface. Trench-Schottky Barrier diodes with breakdown voltage in excess of 1.5kV were demonstrated. First steps for the materials integration of Ga_2O_3 with diamond towards a superjunction based trench-Schottky barrier diode, including epitaxial growth of Ga_2O_3 on single crystal diamond substrates are being reported.

2:15pm **EP+HM+MD-MoA-3 Highly Scaled β-Ga2O3 MOSFET with 5.4 MV/cm Average Breakdown Field and Near 50 GHz fMAX**, ***Chinmoy Nath Saha,*** *A. vaidya,* SUNY at Buffalo*; A. Bhuiyan, L. Meng,* Ohio State University*; S. Sharma,* SUNY at Buffalo*; H. Zhao,* Ohio State University*; U. Singisetti,* SUNY at Buffalo

This letter reports the high performance β-Ga2O3 thin channel MOSFET with T gate and degenerately doped source/drain contacts regrown by Metal Organic Chemical Vapour Deposition (MOCVD). Device epitaxial layer was grown by Ozone MBE. Highly scaled T-gate (LG=160-200 nm) was fabricated to achieve enhanced RF performance and passivated with 200 nm Silicon Nitride (Si3N4). Peak drain current (ID,MAX) of 285 mA/mm and peak trans-conductance (gm) of 52 mS/mm were measured at 10 V drain bias with 23.5 Ω mm on resistance (Ron). Metal/n+ contact resistance of 0.078 Ω mm was extracted from Transfer Length Measurements (TLM). Channel sheet resistance was measured to be 14.2 Kiloohm/square from cross bar structure. Based on TLM and cross bar measurements, we determined that on resistance (Ron) is possibly dominated by interface resistance between channel and regrown layer. Different growth methods originating from MBE channel layer and MOCVD regrown n++ layer can cause this high interface resistance. A gate-to-drain breakdown voltage(V_{DG}) of 192 V is measured for L_{GD}= 355 nm resulting in average breakdown field (E_{AVG}) of 5.4 MV/cm. This $E_{AVG}$is the highest reported among all sub-micron gate length lateral FETs. And highest overall without using any intentional field plate techniques. Current gain cut off frequency (f_T) of 11 GHz and record power gain cut off frequency (f_{MAX}) of approximately 48 GHz were extracted from small signal measurements. f_T is possibly limited by DC-RF dispersion due to interface traps which need further investigation. We observed moderate DC-RF dispersion at 200 ns pulse width (for both output and transfer curve) which can corroborate our theory. We recorded f_T.V_{BR} product of 2.112 THz.V for 192 V breakdown voltage which is similar to GaN HEMT devices. Our device surpasses the switching figure of merit of Silicon because of low on resistance and high breakdown voltage, and competitive with mature wide-band gap devices. Proper surface cleaning between channel and regrowth layer and sub-100 nm T gate device structure can pave the way for better RF performance.

2:30pm **EP+HM+MD-MoA-4 Demonstration of a β-Ga_2O_3 Lateral Diode Full-Wave Rectifier Monolithic Integrated Circuit**, ***Jeremiah Williams,*** *J. Piel, A. Islam, N. Hendricks, D. Dryden, N. Moser,* Air Force Research Laboratory, Sensors Directorate*; W. Wang,* Wright State University*; K. Liddy, M. Ngo,* Air Force Research Laboratory, Sensors Directorate*; N. Sepelak,* KBR Inc.*; A. Green,* Air Force Research Laboratory, Sensors Directorate

Beta Gallium Oxide (Ga_2O_3) is well positioned excel in high power density applications due to its wide band gap, critical field strength, multiple shallow donor species, and melt grown native substrates. Monolithic integrated circuits (ICs) can advance Ga_2O_3 by reducing the size, weight, and connectivity parasitics of components. Lateral topologies with thin epitaxy on insulating substrates enable simple fabrication and integration of RF components. This work utilizes this system to demonstrate a fundamental circuit, the diode full-wave rectifier, with an accompanying design study of the interdigitated lateral diode topology.

The devices (Fig. 1) are fabricated from a 65 nm Si-doped Ga_2O_3 epitaxial layer grown by MBE on a Fe-doped Ga_2O_3 substrate. Epitaxy carrier concentration is measured to be 2×10^{18} cm^{-3} from C-V test structures (Fig. 2). The cathode is a Ti/Al/Ni/Au Ohmic contact annealed at 470 °C. The devices are isolated with a BCl_3 ICP mesa etch. A field-plate and surface passivation oxide of 80 nm thick Al_2O_3 is deposited by ALD. The anode is a Ni/Au Schottky contact. A full-wave rectifier and 16 diode variations are evaluated. The diodes have square and rounded contacts; anode finger counts of 1, 2, 4, and 8; and anode-cathode lengths ($L_{A\text{-}C}$) of 5, 7, and 12 µm. Anode length is 4 µm and width is 48 µm. The diodes in the rectifier have round contacts, 4 anode fingers, and 12 µm $L_{A\text{-}C}$ (Fig. 3). The rectifier is measured on-chip with micro probes. An AC signal is generated with a high-voltage amplifier and measured on an oscilloscope. The output of the rectifier to a 47 kΩ load is measured differentially, using a voltage divider to protect the oscilloscope from voltage spikes (Fig. 4).

The rectifier successfully demonstrates full-wave rectification of sine waves up to 144 V_{rms} (205 V peak) and 400 Hz (Fig. 5). The rectifier demonstrates 83 % efficiency and 0.78 W peak power. To the authors' knowledge, this is the first demonstration of a diode full-waver rectifier IC in Ga_2O_3. From the lateral diode design study, rounded contacts improve the average breakdown voltage (V_{bk}) by 20% (+41 V) without effecting specific on-resistance ($R\text{-}_{on,sp}$) (Fig. 6). The number of anode fingers does not statistically affect V_{bk}, and improves average $R\text{-}_{on,sp}$ by 18% (-0.45 mΩ-cm^2) at eight (Fig. 7). Scaling $L_{A\text{-}C}$ to 5, 7, and 12 µm also scales average $R_{on,sp}$ to 2.0, 2.9, and 8.6 mΩ-cm^2. Average V_{bk} scales as well, but with no change between 5 and 7 µm $L_{A\text{-}C}$ (248, 242, and 341 V) (Fig. 8). The J-V characteristics of a single diode (round contacts, eight fingers, 5 µm $L_{A\text{-}C}$) are included in Fig. 9.

2:45pm **EP+HM+MD-MoA-5 Improved Breakdown Strength of Lateral β-Ga_2O_3 MOSFETs Using Aerosol-Spray-Printed hBN-BCB Composite Encapsulation**, ***Daniel Dryden,*** Air Force Research Laboratory, Sensors Directorate*; L. Davidson,* KBR, Inc.*; K. Liddy, J. Williams, T. Pandhi, A. Islam, N. Hendricks, J. Piel,* Air Force Research Laboratory, Sensors Directorate*; N. Sepelak,* KBR, Inc.*; D. Walker, Jr., K. Leedy,* Air Force Research Laboratory, Sensors Directorate*; T. Asel, S. Mou,* Air Force Research Laboratory, Materials and Manufacturing Directorate, USA*; F. Ouchen,* KBR, Inc.*; E. Heckman, A. Green,* Air Force Research Laboratory, Sensors Directorate

Beta gallium oxide (β-Ga_2O_3) has shown promise for high-voltage power devices and power switching due to its large critical field strength E_c estimated at 8 MV/cm [1]. Dielectric passivation and testing under Fluorinert immersion [2] are used to increase breakdown voltage V_{bk} and avoid air breakdown, respectively, with the highest V_{bk} lateral Ga_2O_3 devices using polymer passivation [3]. The polymer benzocyclobutene (BCB) exhibits high dielectric strength, low parasitics, and good manufacturability [4,5]. It may be loaded with hexagonal boron nitride (hBN), improving thermal conductivity, dielectric response, and mechanical durability [6]. Coatings can be applied via aerosol jet printing, allowing multiple experimental conditions across devices on a single sample. Here, lateral β-Ga_2O_3 MOSFETs encapsulated with hBN-loaded BCB (hBN-BCB) which exhibit significantly enhanced V_{bk} compared to devices encapsulated with BCB alone or without encapsulation.

Si-doped β-Ga_2O_3 was grown epitaxially on a semi-insulating, Fe-doped (010) Ga_2O_3 substrate via molecular beam epitaxy to a nominal thickness of 65 nm and a doping of 2.8+-0.2x10^{17} cm^{-3}. Ti/Al/Ni/Au ohmic contacts were deposited and annealed at 470 °C for 60 s in N_2. Ni/Au gates were deposited on a gate oxide of 20 nm Al_2O_3, followed by a passivation oxide of 85 nm Al_2O_3. Thick Au contacts were formed using evaporation and electroplating. Devices with BCB or hBN-BCB were encapsulated using an Optomec AJ200 aerosol jet printer. Inks consisted of Cyclotene 4022-35, cyclohexanone and terpineol, with or without hBN.

V_{bk} was tested under air or Fluorinert (Figure 2). Devices tested under Fluorinert, BCB, and BCB plus Fluorinert showed a 1.7x improvement in V_{bk} over air. Devices with hBN-BCB showed an improvement of 3.7x over air and 1.35x over BCB alone. The hBN-BCB-coated devices (N=6) show significant improvement in V_{bk} over the devices coated BCB alone (N=3) with p<0.011 (single-tail heteroscedastic T-Test).

Device performance of the highest-V_{bk} device are shown in Figure 3. The device, before encapsulation, had R_{on} of 683 Ω·mm, I_{max} of 3.42 mA/mm, $G_{m,peak}$ of 1.14 mS/mm, V_{th} of -3.8 V, V_{off} of -6.5 V, and V_{bk} of 951 V ($E_{crit,avg}$ 1.23 MV/cm). Device performance was unaffected by hBN-BCB encapsulation (Fig. 3b) excepting a change in V_{off} to -8 V. No significant gate leakage was observed during device operation or breakdown. Breakdown likely occurred due to peak fields exceeding the E_{crit} of one or more materials at the drain-side edge of the gate. These results provide a significant improvement over existing encapsulation approaches in β-Ga_2O_3 lateral MOSFETs.

3:00pm **EP+HM+MD-MoA-6 Wafer-Scale β-Ga_2O_3 Field Effect Transistors with MOCVD-Grown Channel Layers**, ***Carl Peterson***, University of California Santa Barbara; *F. Alema,* Agnitron Technology Incorporated; *Z. Ling, A. Bhattacharyya,* University of California Santa Barbara; *S. Roy,* University of California at Santa Barbara; *A. Osinsky,* Agnitron Technology Incorporated; *S. Krishnamoorthy,* University of California Santa Barbara

We report on the growth, fabrication, and wafer-scale characterization of lateral high-voltage MOSFETs with ~120-160 mA/mm on current on a large area 1" Synoptics™ insulating substrate. A ~170nm Si-doped β-Ga_2O_3 channel with an electron concentration of ~3 x 10^{17} cm^{-3} was grown via metalorganic chemical vapor deposition (MOCVD) on a 1" Fe-doped (010) bulk substrate which was subjected to a 30min HF treatment prior to growth. The growth was done using Agnitron Technology's Agilis 700 MOVPE reactor with TEGa, O_2, and Disilane (Si_2H_6) as precursors with Ar as the carrier gas. A ~210nm unintentionally doped (UID) buffer layer was grown on top of the substrate. The source and drain ohmic contacts were selectively regrown and patterned with a BCl_3 Reactive Ion Etch (RIE) and HCl wet clean. n^+ β-Ga_2O_3 was then grown via MOCVD using Silane (SiH_4) as the silicon precursor and a Ti/Au/Ni Ohmic metal stack was deposited on the regrown regions. A 30nm Al_2O_3 gate dielectric was deposited via ALD at 300C. Lastly, a Ni/Au/Ni gate metal was deposited. The channel sheet charge was measured to be uniform across the wafer (4.6 x 10^{12} cm^{-2} ± 0.6 x 10^{12} cm^{-2}), estimated from the MOSCAP C-V characterization (V_{GS} of +10V (accumulation) to pinch-off). The output and transfer characteristics were measured across the wafer for devices with 1/1.5/1 µm $L_{GS}/L_G/L_{GD}$ dimensions. The pinch-off voltage had a large variation across the wafer (-30 ± 15V). The apparent charge profile from the C-V curves indicates the presence of a parasitic channel at the substrate-epilayer interface which is distributed non-uniformly across the wafer. The on-current (I_D) measured across the wafer was more uniform about 140 ± 20 mA/mm (V_{GS} = +10 V, V_{DS} = 15 V). CV measurements and transfer characteristics indicate a significant density of slow traps (negatively charged) at the dielectric/semiconductor interface, leading to a repeatable shift in the transfer curve from the 2nd scan onward. The MOSFET devices were measured without any field plating or passivation in Fluorinert and the three-terminal destructive breakdown voltages for 5µm and 20µm L_{GD} were 0.65 and 2.1 kV, respectively. Demonstration of wafer-scale growth, processing, and characterization of MOSFETs on a domestic bulk substrate platform reported here is a key step highlighting the technological potential of beta-Gallium Oxide. Acknowledgments: We acknowledge funding from II-VI Foundation, UES Inc. and discussions with AFRL.

3:15pm **EP+HM+MD-MoA-7 Modelling of Impedance Dispersion in Lateral β-Ga_2O_3 MOSFETs Due to Parallel Conductive Si-Accumulation Layer**, ***Zequan Chen***, *A. Mishra, A. Bhat, M. Smith, M. Uren,* University of Bristol, UK; *S. Kumar, M. Higashiwaki,* National Institute of Information and Communications Technology, Japan; *M. Kuball,* University of Bristol, UK

Off-state leakage currents in lateral β-Ga_2O_3 FET devices have previously been attributed to the presence of unintentional Si (n-type) at the interface between epitaxial layer and the substrate[1-5], i.e. a parallel leakage conducting channel. Fe-doping (>$10^{19}$$cm^{-3}$) near the surface of the β-Ga_2O_3 substrate, followed by thermal annealing, has been proven to compensate the unintentional Si impurities, to some degree, thereby reducing leakage current in devices; however, elevated off-state currents and low on-off ratios are still observed in these devices[5]. This work is to provide an analytical model to describe the observed device frequency dispersion due to parallel conductive Si-accumulation layers. Particularly, the dispersion is not associated with active traps as generally believed[6-8].

Lateral β-Ga_2O_3 transistors here were processed on a MBE-grown epitaxial layer on Fe-surface-implanted semi-insulating β-Ga_2O_3 substrates, followed by thermal annealing[5](Fig.1). The transfer characteristics of the device (Fig.2) reveals a large off-state leakage drain current (10^{-6}A/mm) and a small gate leakage current (10^{-12}A/mm). The gate-source capacitance-voltage (C_{GS}) and equivalent conductance-voltage (G_{GS}) profiles between 1kHz and 1MHz (Fig.3) reveal a background dispersion with frequency that is nearly independent of applied gate bias.

An equivalent circuit model is built for explaining impedance dispersion (Fig.4). The parallel leakage path along the entire UID/substrate interface due to Si contaminants provides a coupling path between channels and the probe pads, which are included in the analysis of the device. Therefore, the total capacitance (C_{GS}) will be the "ideal" capacitance (C_{ideal}) superimposed by the contributions from the capacitance and resistance underneath the gate pad(C_{GP}, R_1, C_1), the resistance of the parallel leakage path (R_s), and the capacitance and resistance under the channel (R_2, C_2). Utilizing this model, the measured C_{GS} and G_{GS} are well fitted (Fig.5). The exclusion of traps in the model indicates parallel coupling, instead of traps, should predominantly account for observed frequency dispersion. Moreover, from the extracted R_s in Table.1, the Si concentration at epi/substrate interface is estimated around 1×$10^{18}$$cm^{-3}$, which agrees with that measured from SIMS (Fig.1). This work provides an understanding of the electrical impact of the parallel leakage path of β-Ga_2O_3 devices at moderate frequencies. The signal generated by the parallel leakage can mislead impedance measurements, affecting further analysis such as D_{it} extraction in β-Ga_2O_3 MOSFETs.

Advanced Characterization Techniques
Room Bansal Atrium - Session AC-MoP

Advanced Characterization Techniques Poster Session I

AC-MoP-1 Photoluminescence Mapping of Gallium Oxide*, Matthew McCluskey,* Washington State University

Photoluminescence (PL) spectroscopy is an important method to characterize dopants and defects in gallium oxide. Common features in the PL spectrum include the intrinsic UV band, blue and green bands that involve donor-acceptor pairs, and red emission due to Cr^{3+} impurities. PL mapping with excitation wavelengths ranging from 266 to 532 nm reveals the spatial distribution of these features with micron resolution. Damage due to high-intensity laser pulses results in significant changes in the intensity and energy of the UV band. In Czochralski-grown β-Ga_2O_3:Fe, the Cr^{3+} emission intensity shows striations that are attributed due to inhomogeneities during growth. In addition to defects in the bulk, PL microscopy has revealed several specific defects on the surface. Some of these localized centers are very bright UV emitters. Raman scans of these bright emitters revealed hydrocarbon peaks, which may point toward the origin of the light emission.

AC-MoP-2 Linearly Polarized UV, Blue, and IR Photoluminescence from β-Ga_2O_3*, J. Cooke, M. Lou, Michael Scarpulla,* University of Utah*; A. Bhattacharyya,* University of California, Santa Barbara*; X. Cheng, Y. Wang,* University of Utah*; S. Krishnamoorthy,* University of California, Santa Barbara*; B. Sensale-Rodriguez,* University of Utah

An ultra-wide bandgap of 4.8 eV makes b-Ga_2O_3 a promising material for power devices and ultra-violet (UV) optoelectronics such as UV-transparent electrodes and solar-blind photodetectors. It is well-known that the optical absorption of b-Ga_2O_3 is anisotropic, having different threshold energies for different incident linear polarizations. Due to its low symmetry, the polarization of the emitted photoluminescence (PL) of b-Ga_2O_3 should also be polarized; but this phenomenon which could allow distinguishing between point defects based on their structure has received much less attention. Polarized emission has been predicted and measured to be strongly related to self-trapped holes (STHs) involving O displacements, impurities, and doping. The reported typical b-Ga_2O_3 PL is composed of UV, blue, green, and red main emission bands. Previously-reported PL has discussed excitation polarization-dependent PL, but there has been no discussion of polarized PL emission which we have found also to be polarization dependent.

Herein we report the emission polarization dependence of various high-crystalline-quality melt-grown bulk b-Ga_2O_3samples. It was found that (

We also observed polarized emission for Fe-doped bulk b-Ga_2O_3 samples. Both the b-orientation and [102]-orientation showed red PL with different intensities. Whereas UV, blue, and green PL in UID and Sn-doped samples come from band transition recombination, red PL in Fe-doped samples comes from Cr^{3+}. Therefore, the causes of this emission polarization dependence are different, potentially caused by orbitals within the Cr^{3+}.

AC-MoP-3 Non-Uniformity and Hysteresis of Capacitance-Voltage Doping Profiling in B-Ga_2O_3*, Jian Li,* *A. Charnas, B. Noesges, A. Neal, T. Asel, Y. Kim, S. Mou,* Air Force Research Laboratory, Materials and Manufacturing Directorate, USA

Doping and defects – the important aspects of b-Ga2O3 technology development – are entangled in both their underlying physics and their electrical characterization. Doping uniformity is expected to be key to the feasibility and yield of larger-scale manufacturing of b-Ga2O3-based electronics. This work is concerned with vertical doping uniformity, which is closely tied to present-day challenges such out diffusion of compensating impurities (e.g., Fe and Mg) and interfacial accumulation of doping impurities (e.g., Si). The capacitance-voltage(CV) measured doping profiles of b-Ga2O3 materials by this work and others often show a non-uniformity varying from 15% to 140% over the depth of 100s of nm. The ubiquity of this observation and its indifference of the growth and doping methods are inexplicable from sheer growth point of view therefore warrant a close scrutiny.

The apparent doping profile non-uniformity in a Schottky junction may be accompanied by the observation of CV hysteresis, which shares a common electrostatic basis underlying the threshold voltage instability in field-effect transistors. Irmscher et al. in 2013 reported CV hysteresis in a b-Ga2O3 Schottky diode without accompanying analysis but the subject of that report was on deep levels therefore hinting their implicit role in CV hysteresis. Indeed, works in earlier decades have proven deep states as the origin of CV hysteresis, which manifests the difference of equilibrium and non-equilibrium CV scans. To date, defects in b-Ga2O3 have been detected and characterized by Hall, DLTS, and its variants such as DLOS and admittance spectroscopy. This work explores the case of using illumination-less steady-state room-temperature CV technique for dual-purpose investigation of doping and defect in b-Ga2O3.

We investigate the relationship between doping non-uniformity and carrier dynamics in deep levels in b-Ga2O3. We speculate that the carrier density non-uniformity is in part contributed by an artifact due to carrier emission from deep levels and seek experimental evidences from analytical electrostatic modeling of hysteresis observed in cyclic CV measurements. We aim to separate the contributions of doping and deep levels to more accurately quantify their respective parameters, i.e., doping density and spatial distribution for the former, and energy, density, and capture cross-section for the latter. The materials under investigation include bulk substrates and MBE and MOCVD grown epitaxial layers. We will discuss the implication of our findings on MOSFET operation for power electronic applications.

AC-MoP-4 Scanning Transmission Electron Microscopy (S/TEM) Investigation of γ-Ga_2O_3 Defective Layers In Aluminum and Scandium Alloyed β-Ga_2O_3*, Andrew Balog,* The Pennsylvania State University*; A. Chmielewski,* CEMES-CNRS, France*; R. Lavelle, L. Miao,* The Pennsylvania State University*; J. Jesenovec, B. Dutton,* Washington State University*; C. Lee, E. Ertekin,* University of Illinois at Urbana Champaign*; J. McCloy,* Washington State University*; N. Alem,* The Pennsylvania State University

Beta gallium oxide (β-Ga_2O_3) has gained interest recently as an attractive candidate for high power electronics and extreme environment applications. Possessing a monoclinic structure (space group C2/m), the anisotropic unit cell creates a unique combination of properties. Most important among these is a band gap around 4.8 eV, 1.4 eV greater than the most widely studied UWBG semiconductor, GaN. This results from the presence of tetrahedral and octahedral gallium sites, as well as three inequivalently coordinated oxygen sites. β-Ga_2O_3 suffers from a low thermal conductivity an order of magnitude below common UWBG and power semiconductor materials, as well as a lack of achievable p-type doping. However, the material's most fundamental constraint is insufficient knowledge about defect formation, behavior, and their impact on properties. Recent attempts at alloying β-Ga_2O_3 with scandium and aluminum shows promise mainly in increasing β-Ga_2O_3's band gap, as the monoclinic phases of Sc_2O_3 and Al_2O_3 demonstrate increases up to 5.48 eV and 7.24 eV, respectively. Increasing the band gap via alloying is vital for producing devices in higher critical field applications. However, the role these elements play in defect formation is still not well understood.

Using Scanning/Transmission Electron Microscopy (S/TEM) imaging and spectroscopy, we study how the addition of scandium and aluminum can change the atomic and electronic structure of β-Ga_2O_3. In addition, we identify a nanometer-scale layer of γ-Ga_2O_3 at the surface of a Czochralski-grown single-crystal of β-Ga_2O_3. S/TEM and the suite of tools it provides such as electron energy loss spectroscopy (EELS) and energy dispersive spectroscopy (EDS), also allows for probing local electronic states around defects and general compositional mapping. This provides further information on the environment around defects and their impact on local structure. Using S/TEM imaging we investigate how the γ polymorph of Ga_2O_3 forms as a thin film on the surface of β-Ga_2O_3, while the local bonding environment is uncovered by studying variations in the oxygen EELS K edge. Understanding the formation and structure of this defect phase is vital for improvement of processing and growth techniques, while also allowing for the study of the role alloys play in the defect formation process.

Bulk Growth
Room Bansal Atrium - Session BG-MoP
Bulk Growth Poster Session I

BG-MoP-1 MOCVD Development for Growth of Ga_2O_3 Over Large Areas, ***Muhammad Ali Johar**, A. Feldman, G. Provost, K. Vasudevan,* Structured Materials Industries, Inc*; L. Lyle,* Pennsylvania State University*; L. Porter,* Carnegie Mellon University, USA*; A. Popp,* Leibniz-Institut für Kristallzüchtung (IKZ)*; G. Tompa,* Structured Materials Industries, Inc

Growth of high crystal quality gallium oxide (Ga_2O_3) at large production scale throughput is not available in the market due to (a) a ready high-volume supply of large wafers for homoepitaxy, (b) MOCVD tools explicitly configured for large area MOCVD growth of Ga_2O_3 homo- or heteroepitaxy. One of the primary factors is the unavailability of manufacturing scale substrates and growth tools.

Our company "Structured Materials Industries, Inc, (SMI)" has designed, sold, and fielded several Ga_2O_3 MOCVD growth tools as well as adapted several pre-existing (for different materials) tools to grow Ga_2O_3 and operated in-house tools for growth on single (cm^2 scale, 50mm, 100mm, 150mm, and 200mm) and multiple wafer tools (3×50mm, 19×50mm, and 38×50mm wafer diameters) or multiple 100mm) depositions. These tools have operated using a range of heating systems – induction, radiant filament, and lamps to operate over a range of growth temperatures (~400°C to ~1100°C) using a multiple of binary and alloy growth precursors (O_2, N_2O, H_2O, TEGa, TMGa, TMIn, TMAl, TEAl, $GaCl_3$), process enhancers such as HCl, and dopants (SiH_4, TEOS, TMSn) and are compatible with a wide range of other elements.

The results of these works have led SMI to refine a series of reactors for research to production applications – spanning single to multiple wafer tools employing a multiple of growth parameters and heater types. In this presentation, we will review our series of reactor designs and how they are best applied – for example few through multiple small or large wafer epitaxy is best produced using advanced patented (US7573004 B1) high temperature oxide compatible designed filaments in rotating disc reactors supporting growth through 900°C whereas very high temperature growth – through 1100°C is best produced using induction heating when such high temperatures are warranted, whereas enclosed filament geometries are best for large single wafer processing. We note that filament heating is sufficient for most applications and can be used to produce uniform temperature heating. Reactor designs, supported by simulations of a variety of parameters, such as gas mixtures, flows, temperatures, pressures, carrier flows, flow rates of precursors, and the gap between showerhead and susceptor, for example, are reviewed along with areas of demonstrated results. Overall, production tool designs are based upon optimized parameters and they are reviewed.

BG-MoP-2 Quality Improvement of Sn-doped β-Ga_2O_3 Single Crystal by Optimizing Temperature Gradient Control in Growth Zone, ***Su-Min Choi**, H. Jang, S. Seo, M. Chae, M. Park, Y. Jang,* Department of Advanced Materials Engineering, Dong-Eui University, Republic of Korea*; Y. Moon, Y. Sung, J. Kang,* AXEL, Republic of Korea*; Y. Shin, S. Bae,* Korea Institute of Ceramic Engineering and Technology, Republic of Korea*; W. Lee,* Department of Advanced Materials Engineering, Dong-Eui University, Republic of Korea

As an ultra-wide bandgap semiconductor(UWBG), β-Ga_2O_3 is a very promising materials for various applications such as UV photodetectors, power rectifiers, gas sensors, MOSFETs, SBDs, and LEDs because β-Ga_2O_3 has a wide bandgap of 4.9eV and a high breakdown voltage of 8MV/cm. Furthermore, since β-Ga_2O_3 is capable of melt growth, it is possible to obtain a higher growth rate and a lower manufacturing cost than other WBG semiconductors such as SiC, GaN, and Diamond.[1,2]

In this study, the quality improvement of Sn-doped β-Ga_2O_3 crystal was systematically investigated with controlling temperature gradient in growth cell of edge-defined film-fed growth (EFG) method. Flat-shaped β-Ga_2O_3crystal ribbons were typically grown by the EFG method. The principal surface and the growth direction were set to be (001) and [010], respectively. To prepare Sn-doped n-type bulk crystals, different amounts of Sn powder were added to Ga_2O_3 source powder. The temperature gradient in growth cell was controlled by changing structure of surrounding refractory materials and using the after-heater(A/H). The doping characteristics and crystal quality of various β-Ga_2O_3 crystal ribbons grown with changing the temperature gradient were systematically analyzed. A phase analysis of β-Ga_2O_3 bulk crystals was performed by Raman analysis, and the quality of the crystals was analyzed by a high-resolution X-ray diffraction (HRXRD). Electrical properties and impurity concentration of unintentionally doped (UID) β-Ga_2O_3 and Sn-doped β-Ga_2O_3 crystals were analyzed using the Hall effect measurement system and the secondary ion mass spectrometry (SIMS), respectively.

High-quality Sn-doped (001) β-Ga_2O_3 crystal with a full width at half maximum (FWHM) of 38 arcsec and an etch pit density (EPD) of 3700/cm^2 was obtained with optimizing temperature gradient. Proper temperature gradient resulted in the reduction of SnO_2 volatilization during the growth process and the uniform distribution of bluish color throughout the entire ribbon. The carrier concentration of ≥10^{18}/cm^3 was obtained on Hall effect measurement.

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BG-MoP-4 Various Crystal Planes and their Characteristics obtained from β-Ga_2O_3 Single Crystal Blocks Grown by the Multi-slit Structure of the EFG Method, *Y. MOON,* AXEL, Republic of Korea*; **HUIYEON JANG**,* Dongeui University, Republic of Korea*; Y. SUNG,* AXEL, Republic of Korea*; S. CHOI, M. CHAE, S. SEO, M. PARK, Y. JANG, W. LEE,* Dongeui University, Republic of Korea*; Y. SHIN, S. BAE,* Korea Institute of Ceramic Engineering and Technology, Republic of Korea*; T. LEE, H. KIM,* Korea Institute of Industrial Technology, Republic of Korea*; J. KANG,* AXEL, Republic of Korea

β-Ga_2O_3 4.9eV 의. It has a wide bandgap and a high breakdown voltage of 8MV/cm, so it is receiving a lot of attention for power device applications. In addition, it has the outstanding advantage of being able to grow a single crystal with a higher growth rate and lower manufacturing cost than other WBG semiconductor materials such as SiC, GaN, and diamond. [1-4] In this study, a β-Ga_2O_3 crystal block with a thickness of 10 mm was grown on an Ir die with a multi-slit structure through an edge-define film-fed growth (EFG) process. The growth direction and main surface of the β-Ga_2O_3 crystal were set to the [010] direction and the (100)/(001) plane, respectively, and the crystal growth rate was set to about 12 mm/h. . The crystalline blocks were annealed in a nitrogen environment to reduce residual stress in the crystals before preparing crystal substrates with different orientations. A chemical mechanical polishing (CMP) process using Hastilite Ditron 3.0 slurry was chosen as the final processing step to create an epi-ready surface of the β-Ga_2O_3 crystal substrate. Raman spectra showed successful growth of β-Ga_2O_3 bulk crystals. Crystal quality was assessed by high-resolution X-ray diffraction (HRXRD). Etch pit density (EPD) and defect types were measured on crystal surfaces etched with H_3PO_4 solution.

Etch pit density (EPD) and defect type were measured on the liquid etched crystal surfaces. A typical Sn-doped Ga 2 O 3 crystal block grown by the EFG method was bluish. The X-ray rocking curve values of the Ga_2O_3 single crystal ribbon depend on the Sn doping concentration and show slightly different values depending on the measurement position in the Ga_2O_3 crystal ribbon, indicating the spatial change of the Ga_2O_3 crystal quality. decision. The crystal quality and surface properties of various β-Ga2O3 crystal substrates with (100), (001), (-201), and (hkl) orientations after CMP process were systematically investigated.

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BG-MoP-5 Investigation of Defects in(100) and (001) β-Ga_2O_3Single Crystal GrownbyEFG Method, *M. Choi,* Korea Institute of Ceramic Engineering and Technology/Pusan National University, Republic of Korea*; **Yun-Ji Shin**,* Korea Institute of Ceramic Engineering and Technology, Republic of Korea*; W. Jeong, T. Gu, A. Shin, S. Cho,* Korea Institute of Ceramic Engineering and Technology/Pusan National University, Republic of Korea*; Y. Moon, J. Kang,* AXEL, Republic of Korea*; W. Lee,* Dong-Eui University, Republic of Korea*; S. Jeong,* Korea Institute of Ceramic Engineering and Technology, Republic of Korea*; S. Harada,* Nagoya University, Japan*; K. Ishiji,* Kyushu Synchrotron Light Research Center, Japan*; H. Lee,* Pusan National University, Republic of Korea*; S. Bae,* Korea Institute of Ceramic Engineering and Technology, Réunion

Gallium oxide (Ga_2O_3) has been highlighted as an emerging material for power semiconductor applications [1]. Recent achievements in bulk substrates and epitaxy pave a way for demonstrating several kV level power

devices. However, various defects in β-Ga_2O_3 such as dislocations, stacking faults, and twin defects have been still issued, requiring further crystal quality with defect analysis.X-ray topography is one of powerful techniques to observe defect distribution in a non-destructive way [2].The etch pit technique destructively visualize the defect distribution of the substrate as it chemically etches down the defect regions with an acid (or base). In this study, we compare the defect characteristics of (100) and (001) β-Ga_2O_3 single crystals grown by edge-defined film-fed growth (EFG).

In experiment, the etch pits of (100) and (001) β-Ga_2O_3 single crystals were formed by wet etching with 85 wt% phosphoric acid (H_3PO_4) solution at 140 °C for 120 min. The profile of etched surfaces was observed using atomic force microscope. In addition, (001)-oriented β-Ga_2O_3 single crystal was analyzed using an X-ray topography (Beamline 09, Synchrotron Radiation Facility SAGA-LS).

Figure 1 shows the AFM images of the etched surface for (100) and (001) surfaces. The etch pit of (100) plane are shallower and narrower compared to (001) plane as the (100) plane is parallel to the dislocation direction and has a cleavage property [3]. The density of the etch pits in the (100) and (001) planes were counted to be ~3.8×10^5 cm^{-2} and ~6.0×10^4 cm^{-2}, respectively. Figure 2 shows the XRT image of (001) β-Ga_2O_3 with a diffraction vector, ***g***=605. It was found that the dominant features were dot, line along [010] direction, and curved line contrasts. The line contrasts are mostly associated with b-axis screw dislocations with Burgers vectors (b) parallel to [010], and the dot contrasts are related to edge dislocations with <001> burgers vectors [4]. In addition, many wandering dislocations are observed on the (001) surface, which show curved contrasts. This defect observation might assist to improve the crystal quality of Ga_2O_3 substrates as we perform further in-depth characterization in the future.

References

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Dielectric Interfaces
Room Bansal Atrium - Session DI-MoP
Dielectric Interfaces Poster Session I

DI-MoP-1 Dielectric Lifetime Enhancement of in-situ MOCVD Al_2O_3 on β-Ga_2O_3 Using Temperature Modulated Deposition*, Saurav Roy, A. Bhattacharyya, 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 deposited using metalorganic chemical vapor deposition (MOCVD) to enhance the dielectric quality and lifetime. The growth of Al_2O_3 is performed after the growth of β-Ga_2O_3 without breaking the vacuum in an Agnitron MOVPE reactor using Trimethylaluminum (TMAl) and Oxygen as precursor gas. The interfacial dielectric layer (First 5nm) is grown at 800 °C to crystallize the interface to have reduced interface trap density and the rest of the dielectric (17nm) is grown at 600 °C. Grazing incident Xray diffraction analysis was performed, and polycrystalline inclusions were observed in the grown Al_2O_3 films. The dielectrics grown at 600 °C exhibited higher interface trap density (D_t=3.2×10^{12} cm^{-2}) and lower breakdown field (E_{BR}=6MV/cm) compared to the dielectric grown at 800 °C (E_{BR}=10MV/cm,D_t=5.4×10^{11} cm^{-2}) characterized using deep-UV assisted CV measurements and the current-voltage characteristics of the MOS capacitors. The temperature-modulated dielectric sample (interfacial layer grown at 800 °C, and the bulk dielectric grown at 600 °C) has higher breakdown strength (E_{BR}=7.7MV/cm) and lower trap density (D_t=1.1×10^{12} cm^{-2}) compared to the dielectric grown at 600 °C. This is possibly due to the interfacial crystallization of the hybrid dielectric due to the initial growth at higher temperature. Time dependent dielectric breakdown (TDDB) was also performed to characterize the long-term reliability of the grown dielectrics. From the Weibull distribution plots of the time to breakdown for four different TDDB stress condition, shape factor β>1 was extracted indicating good statistical uniformity and intrinsic breakdown behavior. The TDDB distribution is much tighter (higher β value) for the 600 °C dielectric, compared to the 800 °C grown dielectric. This is possibly due to the short-range ordering of the 800 °C dielectric compared to the 600 °C dielectric, which reduces the long-term reliability of the dielectric. However, for the hybrid dielectric, the time to breakdown is found to be much tightly distributed compared to both 600 °C & 800 °C dielectric. Based on the E-model, the lifetime of the 800 °C can be extended to 10 years if the dielectrics are stressed at 0.7MV/cm, whereas the hybrid dielectric can be stressed at 3.1MV/cm to have 10 years of lifetime. Thus although the static breakdown voltage and trap densities of the hybrid dielectric are a little inferior compared to the 800 °C dielectric, the long term reliability of the hybrid dielectric is much superior.

Epitaxial Growth
Room Bansal Atrium - Session EG-MoP
Epitaxial Growth Poster Session I

EG-MoP-1 A Study of the Critical Thickness for Phase Transition of α-Gallium Oxide Grown on Sapphire Substrates by MOCVD*, Cheng-Han Lee, C. Gorsak, H. Nair,* Department of Materials Science and Engineering, Cornell University

The ultra-wide bandgap semiconductor material α-Ga_2O_3 exhibits promising potential for applications in next-generation high-power electronics and deep-ultraviolet photodetectors. Its large bandgap of 5.3 eV enables a high breakdown voltage and a potentially high Baliga's figure of merit while its rhombohedral corundum structure allows heteroepitaxy of α-Ga_2O_3 on inexpensive isostructural sapphire substrate. One of the major challenges is achieving thick, phase-pure α-Ga_2O_3 films using metal-organic chemical vapor deposition (MOCVD) due to the metastable nature of α-Ga_2O_3. Metastable α-Ga_2O_3 has a strong tendency to revert back to the thermodynamically stable monoclinic β-Ga_2O_3 phase. This gives rise to the natural question: Can epitaxial growth of single-phase α-Ga_2O_3 with high crystalline quality be achieved via MOCVD and how does the critical thickness of α-Ga_2O_3 films depend on MOCVD growth parameters and different surface orientations of sapphire substrates, and what is the mechanism for phase transformation to β-Ga_2O_3?

In this study, we investigate the critical thickness for structural phase transition of MOCVD-grown α-Ga_2O_3 epitaxial thin films grown on c-, m-, r-, and a-plane sapphire substrates. To ensure high crystallinity and to suppress defect generation, we develop a two-step growth method in which a 10-nm-thick α-Ga_2O_3 low-temperature nucleation layer was deposited at 600°C at a low growth rate of 0.4 μm/hr, followed by a high temperature growth of Ga_2O_3 epilayer with thickness ranging from 100 nm to 1600 nm at 600~800°C with a higher growth rate of 0.7~1.0 μm/hr. X-Ray diffraction (XRD) was utilized to confirm the phase purity of α-Ga_2O_3 films and to evaluate crystalline quality based on rocking curve Full-Width-at Half Maximum (FWHM). We successfully demonstrated that single-phase, highly-crystalline α-Ga_2O_3 films with thickness ~400 nm can be achieved on m-plane sapphire substrate through a low-pressure, low-temperature, and high growth rate heteroepitaxial growth, resulting in one of the highest α-Ga_2O_3 critical thickness ever reported on m-plane α-Al_2O_3 via MOCVD.

This work highlights the importance of selecting suitable differently oriented sapphire substrates for the growth of phase-pure α-Ga_2O_3 epitaxial thin films using MOCVD. We pursue to further increase the critical thickness and aim to delineate the mechanism for phase transformation of α-Ga_2O_3. Thicker films and controllable doping of α-Ga_2O_3 thin films can potentially pave the way for the fabrication of α-Ga_2O_3 based high-power electronic devices.

EG-MoP-2 Epitaxial Growth of β-Ga_2O_3 Films on Mgo Substrate via Mist Chemical Vapor Deposition Method*, Takumi Ikenoue,* Kyoto University, Cronell University, Japan*; Y. Cho, V. Protasenko, C. Savant, B. Cromer,* Cornell University*; M. Miyake, T. Hirato,* Kyoto University, Japan*; M. Thompson, D. Jena, H. Xing,* Cornell University

Gallium oxide (Ga_2O_3) is expected to be a promising material for power devices due to its wide bandgap and high Baliga figure of merit. Various methods of epitaxial growth have been explored for β-Ga_2O_3, including growth on MgO substrates which possess a larger bandgap than β-Ga_2O_3 and sufficient insulation. MgO has the same crystal structure as NiO, which is expected to be a p-type wide-gap oxide semiconductor, and has a small lattice mismatch, making it the most promising candidate for the substrate for epitaxial growth of NiO. Consequently, the growth of β-Ga_2O_3 on MgO is important, particularly for the development of devices that combine NiO and β-Ga_2O_3. We previously conducted a study on the growth of NiO on MgO substrates using mist chemical vapor deposition (CVD). This oxide film growth technique utilizes a solution as a source under atmospheric pressure and is known for its high quality and productivity. By using this method, we showed the ability to not only produce high-quality NiO(001)

single crystals on MgO(001), but also achieve conductivity control by using Li as a dopant. The growth of β-Ga_2O_3 on MgO would lead directly to heterojunction formation with NiO, which has almost the same lattice constant as MgO. Therefore, in this study, we report the growth of β-Ga_2O_3 on MgO(001) substrates using the mist CVD method.

Prior to growth, MgO substrates were ultrasonically cleaned with acetone and methanol. The precursor used for β-Ga_2O_3 growth was gallium acetylacetonate, which was diluted in deionized water at a concentration of 0.020 mol/L. Hydrochloric acid was added for complete dissolution. Growth temperature and time were set at 600 ˚C and 6 minutes respectively.

XRR measurements determined the film thickness to be 80.6 nm with a growth rate of 0.806 μm/h, which is comparable to HVPE. Peaks from β-Ga_2O_3 (400) and β-Ga_2O_3 (600) were observed by the XRD 2θ scan, indicating that (100)-oriented β-Ga_2O_3 was grown. It should be noted that the peak of γ-Ga_2O_3 (400) (at 2θ=43.93°), which was observed in the growth of β-Ga_2O_3 on MgO using PLD and MOCVD, was not observed. With no γ-Ga_2O_3 phase at the interface between MgO and β-Ga_2O_3, it may be possible to fabricate a sharp interface in β-Ga_2O_3 growth on MgO and p-NiMgO. The full width at half maximum of the ωrocking curve from β-Ga_2O_3 (400) was 145 arcsec, indicating high-quality crystal growth. From the ϕ scan, the in-plane orientation was determined to be β-Ga_2O_3 (100)[001] ‖ MgO (001)[110]. In addition, the RSM roughness of the 5x5 μm^2 AFM image was 0.74 nm.

EG-MoP-3 Fluid Analysis of MIST-CVD Chamber for Uniformity Improvement in Gallium Oxide Epitaxial Growth, ***Jungyeop Hong***, *Y. Jung, D. Chun, J. Park, N. Joo, T. Kim,* Hyundai Motor Company, Republic of Korea

Gallium oxide has emerged as a promising material for high-performance electric vehicle and UV application applications. Among the various crystal phases of gallium oxide, the alpha phase has the widest band gap, making it suitable for manufacturing high voltage semiconductor devices. However, the alpha phase cannot be grown by homo-epitaxy, and the method of growing on a foreign substrate is mainly employed.

This paper focuses on the deposition of gallium oxide on wafers and highlights the limitation of the current maximum wafer size to 2 inches. To enable mass productivity, there is a need for equipment and process technologies that can accommodate larger wafer sizes for deposition. The research presented in this study aims to address this challenge by proposing solutions that can potentially contribute to the development of more efficient and cost-effective production processes for gallium oxide-based devices.

The study investigated the challenge of achieving stable uniformity in Ga2O3 epi grown on a 4-inch substrate compared to a 2-inch substrate. To overcome this issue, the authors proposed a fluid analysis of the MIST-CVD chamber to identify potential improvements for achieving better uniformity. This research can contribute to the development of Ga2O3 epi with higher uniformity and quality on larger substrates, which is crucial for its practical applications.

We conducted a study on growing Ga2O3 epi layers on a 4-inch substrate using MIST-CVD equipment. To achieve uniform growth of the epi on the 4-inch substrate, they evaluated the distribution level of the mist using fluid analysis methods. The chamber was modeled, and the mist distribution level was numerically interpreted under various conditions using fluid analysis tools. The optimal epi growth conditions with high mist distribution level and uniformity were derived based on the results. Growth technique was developed to obtain process reproducibility and excellent epitaxy quality even on a 4-inch wafer.

The research demonstrated the up-scale growth of high-quality Ga2O3 epi-layers on sapphire substrates, which could have potential applications in high-power and high-frequency electronic devices. To improve the uniformity of the large substrate, Our group modeled the sample position and gas flow in the Chamber and optimized the process conditions to achieve excellent uniformity. To verify the improvement in the uniformity of the epitaxial deposition, measurements using an Ellipsometer and XRD were performed.

EG-MoP-6 The Effect of Excess Ga on Electron Transport in *β*-Ga_2O_3 Grown via Plasma Assisted Molecular Beam Epitaxy, ***Thaddeus Asel***, *B. Noesges, Y. Kim, A. Neal, S. Mou,* Air Force Research Laboratory, Materials and Manufacturing Directorate, USA

Since the first demonstration of *β*-Ga_2O_3 based devices, there has been significant work done developing epitaxial growth methods for high quality *β*-Ga_2O_3 films. Improvement in the mobility of epitaxial films has been demonstrated in recent years. Additionally, the quantification of defect states in thin films has been performed for several growth techniques, including molecular beam epitaxy (MBE). However, there has yet to be a systematic study of the relationship between the *β*-Ga_2O_3 growth parameters, the electronic transport properties, and the defects present in *β*-Ga_2O_3 films grown via MBE. In this work we investigate the effect of excess Ga beam flux on the electronic properties of *β*-Ga_2O_3 films grown via MBE. Utilizing temperature dependent Hall Effect measurements and a self-consistent fitting of the temperature dependent carrier density and mobility data, we are able to quantify the concentration defect states, including compensating acceptors, deep level impurities, and unintentional donors, present in the epitaxial films. The Ga beam flux can control the oxygen to Ga ratio present in the chamber as our oxygen is held constant for each growth run. This allows for growths that occur in the "oxygen rich" regime where the amount of Ga supplied limits the growth rate and the "gallium rich" regime where the amount of O supplied limits the growth rate. In both regimes the formation of the volatile suboxide Ga_2O occurs, but in the gallium rich regime, the desorption of Ga_2O causes a lower growth rate than that seen in the oxygen rich regime, due to the excess of Ga presence preventing the second reaction step in Ga_2O_3 growth. Two preliminary samples were grown in the gallium rich (Ga Beam Flux = 1×10^{-7} Torr) and oxygen rich (Ga Beam Flux = 6×10^{-8} Torr) regimes. The samples had different doping densities of 4.25×10^{17} cm^{-3} in the gallium rich sample and 2.60×10^{17} cm^{-3} in the oxygen rich sample, this discrepancy is due to an inaccuracy in the Si doping source. The acceptor concentration in the gallium rich sample was calculated to be 7.26×10^{16} cm^{-3} and 4.50×10^{15} cm^{-3} in the oxygen rich sample, a factor of 16 different based on the Ga overpressure. This is likely due to Ga vacancies that can form during the desorption of Ga_2Oduring growth. These results indicate that there is significant impact on the electron transport properties of *β*-$Ga_{2}O_3$ when there is excess Ga present during the growth, and that optimization of growth parameters is needed to optimize the electronic properties of MBE grown *β*-$Ga_{2}O_3$.

EG-MoP-7 Low-Pressure Chemical Vapor Deposition of Ultrawide Bandgap $LiGa_5O_8$ Thin Films, ***Kaitian Zhang***, *L. Meng, H. Huang,* The Ohio State University*; J. Sarker,* University of Buffalo, SUNY*; A. Bhuiyan,* The Ohio State University*; B. Mazumder,* University of Buffalo, SUNY*; J. Hwang, H. Zhao,* The Ohio State University

$LiGaO_2$ represents an ultrawide band gap semiconductor with an energy gap of 5.8 eV. It is considered as a group I-III-VI_2 counterpart of the group II-VI ZnO, and has an orthorhombic crystal structure. The ground state β-$LiGaO_2$ has a $Pna2_1$ space group. It has recently been predicted that $LiGaO_2$ is n-type dopable with Si or Ge and the possible p-type doping is under investigation. $LiGaO_2$ has been considered for piezoelectric and nonlinear optical applications in the past. Bulk growth of single-crystal $LiGaO_2$ has been studied as closely lattice-matched substrate (a = 5.407 Å, b = 6.405 Å and c = 5.021 Å) for GaN epitaxy. However, thin film growth of $LiGaO_2$ is still at an early stage with only PLD growth of $LiGaO_2$ on ZnO template was reported.

In this work, low pressure chemical deposition (LPCVD) of $LiGaO_2$ on various substrates were studied. C-plane sapphire, (010) and (001) $LiGaO_2$ substrates were used in this study. High purity Ga pallets, LiCl powder and O_2 were used as the precursors whereas Ar was used as the carrier gas. The growth temperature was kept at 900 °C. From a series of material characterization, the film grown on top of the (001) $LiGaO_2$ substrate is stabilized with a spinel-cubic structure $LiGa_5O_8$ with a lattice constant of 8.203 Å and space group P4_33-2 (Ga in both tetrahedral and octahedral sites). The spinel-cubic crystal structure of the $LiGa_5O_8$ film was confirmed from the atomic resolution HAADF STEM image and selected area electron diffraction (SAED) pattern. Additionally, the atom probe tomography (APT) measurement on the same sample confirmed a uniform Li distribution and a near-stoichiometric ratio of ~1:5:8 for Li/Ga/O.

$LiGa_5O_8$ has been studied as a phosphor host material when doped with transition metal and rare earth elements. To the best of our knowledge, this work represents the first experimental demonstration of thin film growth of pure $LiGa_5O_8$. Recent theoretical calculations suggest that $LiGa_5O_8$ has an indirect bandgap of approximately 5.7 eV with the direct gap about 0.1 eV higher, which renders $LiGa_5O_8$ a potential ultrawide bandgap semiconductor for power electronics applications.

In conclusion, this investigation explored the LPCVD growth of $LiGaO_2$ thin films on c-sapphire and $LiGaO_2$substrates. The results revealed a successful growth of $LiGa_5O_8$ film on (001) $LiGaO_2$ substrate. Comprehensive growth conditions still need to be mapped to determine the correlation between the growth condition, substrate selection and stabilization of crystal

structure of $LiGa_xO_y$.

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EG-MoP-8 Controlling Si Dopant Profiles in n-type *β*-Gallium Oxide, ***Brenton Noesges***, *Y. Kim, A. Neal, S. Mou, T. Asel,* Air Force Research Laboratory, Materials and Manufacturing Directorate, USA

Oxidation of dopant sources affects dopant vapor pressures which can impact dopant profile uniformity in *β*-Ga_2O_3 grown via plasma-assisted molecular beam epitaxy (PAMBE).[1,2] In this work, we will focus on optimizing uniform dopant profiles in the low Si doping regime (<10^{18} cm^{-3}) of *β*-Ga_2O_3 films since Si doping concentrations show a gradient, increasing toward the surface of *β*-Ga_2O_3 thin films. Si concentrations of ~3x10^{17} cm^{-3} are achievable as demonstrated by secondary ion mass spectroscopy (SIMS). Capacitance-voltage (CV) measurements to extract carrier concentrations agree well with Si concentrations observed in SIMS. We will also look at another aspect of Si incorporation in *β*-Ga_2O_3 that needs consideration when using traditional effusion cells as a Si dopant source. Previous work in PAMBE *β*-Ga_2O_3 growth demonstrated the importance of oxygen plasma power on controlling the background amount of Si present in *β*-Ga_2O_3 films.[3] In this work, we continued to explore sources of unintentional Si accumulation during the PAMBE growth process. The presence of Si at the interface between *β*-Ga_2O_3 substrate and film provides a parasitic conduction channel which is problematic for device performance. Attempts have been made to remove this Si at *β*-Ga_2O_3 interfaces via etching. Our results indicate that removing interfacial Si may not be as simple since Si can re-accumulate during PAMBE processes, thus limiting the effectiveness of pre-growth surface treatments. We created a test sample for SIMS simulating the effects of exposing clean *β*-Ga_2O_3 surfaces to potential sources of Si in a PAMBE system including quartz plasma bulb and dopant Si effusion cells. Exposure to only quartz plasma bulb did not produce Si accumulation at the surface. On the other hand, a growth interrupt that exposed a fresh *β*-Ga_2O_3 to the hot Si source for several minutes produced Si accumulation equal to that of the interfacial Si between substrate and film. These results demonstrate that removing Si prior to loading into PAMBE may be inadequate to remove interfacial Si since Si can be re-introduced from the Si dopant cell during pre-deposition stages like plasma stabilization. This work and results point toward important challenges and potential solutions when creating Si-doped *β*-Ga_2O_3 thin films.

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EG-MoP-9 Silicon-doped *β*-Ga2O3 Films Grown at 1 µm/h by Suboxide Molecular-Beam Epitaxy, ***Kathy Azizie***, *F. Hensling, C. Gorsak,* Cornell University*; Y. Kim,* Air Force Research Laboratory*; N. Pieczulewski,* Cornell University*; D. Dryden,* Air Force Research Laboratory*; M. Senevirathna, S. Coye,* Clark Atlanta University*; S. Shang,* Penn State University*; J. Steele, P. Vogt, N. Parker, Y. Birkhölzer, J. McCandless, D. Jena, H. Xing,* Cornell University*; Z. Liu,* Penn State University*; M. Williams,* Clark Atlanta University*; A. Green,* Air Force Research Laboratory*; D. Schlom,* Cornell University

We report the use of suboxide molecular-beam epitaxy (*S*-MBE) to grow *β*-Ga_2O_3 at a growth rate of ~1 µm/h with control of the silicon doping concentration from 5*10^{16} to 10^{19} cm^{-3}. In *S*-MBE, pre-oxidized gallium in the form of a molecular beam that is 99.98% Ga_2O, i.e., gallium suboxide, is supplied. Directly supplying Ga_2O to the growth surface bypasses the rate-limiting first step of the two-step reaction mechanism involved in the growth of *β*-Ga_2O_3 by conventional MBE. As a result, a growth rate of ~1 µm/h is readily achieved at a relatively low growth temperature (T_{sub} ≈ 525 °C), resulting in films with high structural perfection and smooth surfaces (rms roughness of < 2 nm on ~1 µm thick films). Silicon-containing oxide sources (SiO and SiO_2) producing an SiO suboxide molecular beam are used to dope the *β*–Ga_2O_3 layers. Temperature-dependent Hall effect measurements on a 1 µm thick film with a mobile carrier concentration of 2.7*10^{17} cm^{-3} reveal a room-temperature mobility of 124 cm^2 V^{-1} s^{-1} that increases to 627 cm^2 V^{-1} s^{-1} at 76 K; the silicon dopants are found to exhibit an activation energy of 27 meV. We also demonstrate working MESFETs made from these silicon-doped *β*-Ga_2O_3 films grown by *S*-MBE at growth rates of ~1 µm/h.

EG-MoP-10 Epitaxial Growth of Metastable Ga_2O_3 Polymorphs Using MOCVD and HVPE, ***Jingyu Tang***, *M. Moneck, M. Weiler, K. Jiang, R. Davis, L. Porter,* Carnegie Mellon University

In recent years, there has been an increasing interest in the growth and electronic properties of metastable Ga_2O_3 polymorphs, e.g., κ-Ga_2O_3 with its high predicted spontaneous polarization as a potential ferroelectric material and α-Ga_2O_3 with its wider bandgap and ability to alloy with α-Al_2O_3. The metastable κ-Ga_2O_3 phase can be grown in epitaxial film form on substrates such as 4H/6H-SiC, Al_2O_3, AlN, GaN using vapor phase techniques. The κ-Ga_2O_3 films reported in the literature have varying degrees of phase purity and commonly contain three in-plane rotational domains, although there are some reports of suppressed rotational domains or increased domain sizes when grown on lattice-matched $GaFeO_3$ substrates[1], patterned sapphire[2] and SiH_4 gas introduction[3]. α-Ga_2O_3 films with high dislocation densities have been commonly grown on c-plane sapphire as indicated by the broader full-width-at-half-maxima (FWHM) of the X-ray rocking curves (XRC) of the tilted planes. Film growth techniques such as epitaxial lateral overgrowth4, depositing buffer layers[5] have been implemented to reduce the dislocation density. In this study, nominally phase-pure α-Ga_2O_3 and κ-Ga_2O_3 epitaxial films were grown on vicinal a-plane and c-plane sapphire substrates, respectively, at Carnegie Mellon University using halide vapor phase epitaxy (HVPE) and/or metalorganic chemical vapor deposition (MOCVD). Phase and microstructural characterization studies were conducted using high-resolution X-ray diffraction (HR-XRD), scanning electron microscopy (SEM), and transmission electron microscopy (TEM). The growth of κ-Ga_2O_3 using MOCVD[6] revealed the presence of a 20-60 nm thick transition layer containing a mixture of β- and γ-Ga_2O_3 near the interface. In contrast, there was no detectable β peak or even a β shoulder in the κ-Ga_2O_3 films grown by HVPE. The FWHM of the (004) κ-Ga_2O_3 XRC for the HVPE film was 5x more narrow than that of the MOCVD film with respective values of 0.11° and 0.49°. Comparable FWHM values in the literature for κ-Ga_2O_3 are 0.16° to 0.82°3,7,8. Whereas. α-Ga_2O_3 has been difficult to produce using MOCVD, nominally phase-pure (11-20) α-Ga_2O_3 films with exceptionally low FWHM for (11-20) = 0.034° are readily produced at 650°C using HVPE. In summary, our findings indicate that HVPE growth leads to nominally phase-pure α-Ga_2O_3 and κ-Ga_2O_3 epitaxial films with narrow XRCs, and offers promising avenues for further investigation of the properties of metastable Ga_2O_3 phases.

EG-MoP-11 Pulsed Laser Deposition of α-Ga_2O_3 on M-Plane Al_2O_3: Growth Regime, Growth Process and Structural Properties, ***Clemens Petersen***, University Leipzig, Felix Bloch Institute for Solid State Physics, Semiconductor Physics Group, Leipzig, Germany*; S. Vogt, H. von Wenckstern, M. Grundmann,* University Leipzig, Felix Bloch Institute for Solid State Physics, Semiconductor Physics Group, Germany

Due to its wide band gap of 4.6 eV - 5.6 eV and large predicted breakdown field of 8 MV cm^{-1} [1], much attention is drawn to the ultra-wide bandgap semiconductor Ga_2O_3 for applications in high-power devices. However, besides the well-studied thermodynamically stable monoclinic β-phase of Ga_2O_3, the metastable α-polymorph with corundum structure is rapidly gaining interest in the scientific community. Since it is isostructural to α-Al_2O_3, growth of layers with high structural quality on cost-efficient sapphire substrates is feasible. In particular, m-plane sapphire facilitates the growth of the corundum phase by suppressing c-plane facets on which the β-phase favorably crystallizes [2]. Further, Sn-doped α-Ga_2O_3 thin films grown on m-plane sapphire show electron mobilities of up to 65 cm^2 V^{-1} s^{-1}, which is three times higher than what can be achieved on c-plane cut substrates as reported by Akaiwa *et al*. [3]. To our knowledge, a systematic study of the growth of Ga_2O_3 on m-plane sapphire by pulsed laser deposition (PLD) has not been published to date.

We present phase-pure α-Ga_2O_3 thin films with high surface quality and crystallinity grown on m-plane sapphire using PLD [4]. Therefore, the influence of growth temperature, oxygen background pressure, and film thickness on structural properties is investigated to determine the growth window for phase-pure α-Ga_2O_3. Samples were analyzed using X-ray diffraction, atomic force microscopy, and spectroscopic ellipsometry measurements. A distinct growth window for phase-pure (10.0)-oriented α-Ga_2O_3 at growth temperatures above 450°C and low oxygen partial pressures *p*(O2) of 3×10^{-4} mbar is identified. It was found that for thicker layers (> 200 nm) the growth of monoclinic β-Ga_2O_3 is promoted. This is likely induced by the c-facets of the α-Ga_2O_3 grains, leading to a (010) orientated island growth corroborated by stripe-like features in atomic force microscopy scans and a corresponding in-plane orientation confirmed by x-ray diffraction ϕ-scans. For oxygen partial pressures above 3×10^{-4} mbar and growth temperatures below 530°C, the formation of mixed (10.0) α-

Ga_2O_3 and spinel-defective (110) γ-Ga_2O_3, manifesting as inclusions, was observed independently of the layer thickness. A corresponding phase diagram for Ga_2O_3 growth on m-plane sapphire by PLD is presented.

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EG-MoP-14 High-Quality Power Device Grade β-Ga_2O_3 on 4H-SiC via Metal Organic Chemical Vapor Deposition*, I. Sanyal, A. Nandi,* ***Martin Kuball,*** University of Bristol, UK

Ga_2O_3 suffers from low thermal conductivity which would translate into excessive device temperatures. Integration with high thermal conductivity materials is, therefore, essential to explore. We report epitaxial growth of high material quality β-Ga_2O_3 on 4H-SiC (0001) substrates using MOCVD. Recent reports indicated β-Ga_2O_3 growth on 4H-SiC at a deposition temperature of 650 °C using LPCVD, resulting in rms surface roughness of 2.25 nm and FWHM of 1.3°, and at 700 °C using liquid-injection MOCVD with rms surface roughness of 8 nm. However, we observed formation of incomplete misoriented particles when the layer was grown at a temperature between 650 °C to 750 °C as shown in fig 1. Two steps modified growth method was then adopted where the nucleation layer was grown at 750 °C followed by a buffer layer grown at various temperatures from 750 to 950 °C. Three samples namely S1, S2 and S3 were compared to understand the growth mechanism. S1 and S2 are identical except the bulk layer where the growth temperature was 920 °C and 950 °C respectively. S1 shows partly coalesced surface with misoriented grains or nano-crystallites as shown in fig.2. Whereas, S2 forms fully coalesced surface without any pseudohexagonal domains as shown in fig. 3. XRD 2θ-ω scan confirms β-polymorph of Ga_2O_3 with dominant peak in (-201) direction and FWHM of 0.9°. One of the challenges in growing β-Ga_2O_3 on SiC substrate with O_2 source at high temperature is the formation of amorphous SiO_2 layer on the growth surface that results in poor crystal quality. Si-terminated 4H-SiC/ β-Ga_2O_3interface is highly sensitive to O_2 due to its lowest migration energy. O-terminated β-Ga_2O_3 in (-201) direction and Si-terminated 4H-SiC in (0001) direction offer lowest relaxation energy and thus highest stability by forming covalent bond between Si-O at the interface. Furthermore, the nucleation layer grown at lower temperatures is polycrystalline in nature with a high density of defects that propagate into the top layer. Instead of growing a thin nucleation layer at a fixed lower temperature, we implemented a new 'ramp-growth' technique in S3 where the growth of the nucleation layer starts at 780 °C and the temperature linearly increases to 950 °C within three minutes followed by the growth of the buffer layer at 950 °C. As can be seen in fig. 4, the surface roughness reduced to 3 nm with FWHM as low as 0.79°, comparable to the most mature β-Ga_2O_3 heteroepitaxy on sapphire using MOCVD, greatly advanced to currently available Ga_2O_3 on SiC, paving the way for the development of high voltage device fabrication with improved thermal property.

Electronic and Photonic Devices, Circuits and Applications Room Bansal Atrium - Session EP-MoP

Electronic and Photonic Devices, Circuits and Applications Poster Session I

EP-MoP-2 Anisotropy Nature of NiO_x/β-Ga_2O_3*p-n* Heterojunctions on (-201), (001), and (010) β-Ga_2O_3 Substrates*, Dinusha Herath Mudiyanselage,*** *D. Wang, H. Fu,* Arizona State University

Recently, β-Ga_2O_3 has been extensively studied for power, optical, and RF electronics due to its large bandgap of 4.9 eV and high breakdown field of 8 MV/cm. However, most of the demonstrated devices are unipolar due to the lack of *p*-type Ga_2O_3, such as FETs and SBDs. This is primarily attributed to the absence of shallow acceptors in Ga_2O_3. As a solution, other *p*-type materials, such as NiO_x, have been utilized to produce β-Ga_2O_3 based *p-n* heterojunctions. Several NiO_x/β-Ga_2O_3 devices, such as *p-n* diodes and junction barrier Schottky diodes, have been demonstrated with excellent electrical properties. Moreover, due to its highly asymmetric monoclinic crystal structure, β-Ga_2O_3 exhibits anisotropic properties along different crystal orientations. However, the impacts of different β-Ga_2O_3 crystal orientations on NiO_x/β-Ga_2O_3*p-n* heterojunction are still unclear. In this work, we perform a systematic study of NiO_x/β-Ga_2O_3*p-n* heterojunctions on (-201), (001), and (010) crystal orientations. The EFG-grown β-Ga_2O_3 substrates were acquired with a similar *n*-type doping concentration and thickness. First, the substrates were cleaned using acetone, IPA, and DI water. The Ti/Au (20/130 nm) back contacts were deposited by E-beam evaporation followed by rapid thermal annealing at 500 °C in N_2. Then, standard photolithography was performed to define patterns for deposition of NiO_x and the anode. 200 nm NiO_x and the anode Ni/Ti/Au (20/15/100 nm) were deposited using E-beam evaporation, followed by a liftoff process to isolate devices. I-V and C-V measurements were performed using a 4200 SCS semiconductor parameter analyzer. All devices show an excellent rectification with on/off ratio >10^9. I-V measurements indicate a turn-on voltage of 2.09, 2.22, and 2.50 V, an ideality factor of 1.95, 2.03, and 2.13, and an on-resistance of 2.92, 1.55, and 6.50 mΩ.cm^2 for (-201), (001), and (010) devices, respectively. C-*f* measurements indicated an interface state density of 4.3 × 10^{10}, 7.4 × 10^{10}, and 1.6 × 10^{11} $eV^{-1}cm^{-2}$ for (-201), (001), and (010) plane devices, respectively. Furthermore, the reverse recovery of the diodes shows a slight difference between (-201) [or (001)] and (010) devices due to the anisotropic nature of β-Ga_2O_3. These differences in the electrical properties are attributed to the different atomic configurations, the density of dangling bonds, and conductivity-modulated hole injection into β-Ga_2O_3. Further investigation through temperature-dependent measurements will reveal more information about the anisotropic nature of NiO_x/β-Ga_2O_3*p-n* heterojunctions.

EP-MoP-3 Ultrathin Films of Amorphous Gallium Oxide for Ultra-Fast Solar-Blind Photodetectors*, Damanpreet Kaur, M. Kumar,* Indian Institute of Technology Ropar, India

In addition to stable and meta-stable crystalline phases of Ga_2O_3, its amorphous phase is also being explored for various applications owing to its technological advantage like room temperature and large area growth for next generation solar-blind photodetectors .[1] But being often sub-stoichiometric and replete with oxygen vacancies, performance of amorphous thin film PDs is far below their crystalline counterparts. Hence, novel methods and techniques need to be adopted to improve performance of such devices.[2] Herein, we report one such method where ultra-thin films of amorphous Ga_2O_3 are deposited on nanopatterned SiO_2 coated Si substrate. Controlled nanopatterns or ripple formation is carried out by irradiating SiO_2/Si substrate with 500eV Ar^+ ions for variable times. Morphology of ripples formed on substrate is studied using AFM images to calculate the characteristic wavelength and Power Spectral Density. Amorphous Ga_2O_3 (~5nm) is then sputtered onto these rippled substrates using RF Magnetron Sputtering at room temperature. Uniformity of Ga_2O_3 is confirmed by EDX elemental mapping studies. Reflectance measurements were carried out using UV-Vis spectroscopy and results showed lower reflectance as compared to non-rippled because of the enhanced absorption due to multiple scattering by the substrate and enhanced surface area. FDTD was used to simulate reflectance measurements which are well in agreement with experimental results.

The performance of subsequently fabricated photodetectors showed that conformally coated devices had an enhanced performance as compared to non-rippled "bare" device. The solar-blind PDs show an increase in the responsivity from ~3 mA $W^{-1}$to 433 mA W^{-1} – an increment of more than 140 times at +5V. For the response times, bare device shows slow rise/fall time of 0.37s /0.39s whereas the conformal devices showed an ultrafast rise time of 896µs and fall time of 710µs, respectively, to 254 nm incident light. The detailed analysis showed that the device performance can be attributed to the incorporation of elemental Si from the substrate below, the presence of which is confirmed by XPS. This study shows how amorphous Ga_2O_3 films can be used to fabricate ultra-fast devices, especially for next-generation solar-blind PD applications.

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Heterogeneous Material Integration
Room Bansal Atrium - Session HM-MoP

Heterogeneous Material Integration Poster Session I

HM-MoP-1 Characterization of Sputtered P-Type Nickel Oxide for Ga_2O_3 Devices, ***Joseph Spencer,*** Naval Research Laboratory*; Y. Ma, B. Wang, M. Xiao,* Virginia Tech*; A. Jacobs, J. Hajzus,* Naval Research Laboratory*; A. Mock,* Weber State University*; T. Anderson, K. Hobart,* Naval Research Laboratory*; Y. Zhang,* Virginia Tech*; M. Tadjer,* Naval Research Laboratory

β-Ga_2O_3 is a promising UWBG (E_G = 4.8 eV) material in the field of power electronics. However, the flat valence band of β-Ga_2O_3 has prevented the realization of p-Ga_2O_3. Without shallow acceptor dopants and p-type conductivity in β-Ga_2O_3, the ability to fabricate high power homojunction devices (PN and JBS diodes) with appropriate field mitigation (guard rings, JTE) is not possible. While other WBG materials such as SiC and GaN can be doped to form p-type conductivity, Ga_2O_3 must rely on a heterojunction. A heterojunction device often exhibits interface traps that negatively impact device performance.

Nickel Oxide (NiO) is a cubic WBG (3.7 eV) p-type semiconductor [1] that is stable at room temperature and forms a favorable band offset to Ga_2O_3 [2]. Reactive ion sputtering is often used to deposit NiO thin films on Ga_2O_3; in our case, a NiO target was utilized to sputter at room temperature. Small changes in sputtering conditions and parameters such as deposition power and pressure, results in widely varying electrical and material properties of the NiO thin films, making characterization challenging. While accurate and repeatable values of N_A can be challenging, a better understand is crucial for device fabrication.

In this work we characterized room-temperature sputtered NiO thin films using electrical methods, ellipsometry, and X-ray photoelectron spectroscopy (XPS) in an attempt to understand the properties of the films. Variations in sputtering power, pressure, and oxygen partial pressure resulted in wide ranging electrical parameters. Most deposition conditions (Table I) result in low mobility (~1 $cm^2/(V{\cdot}s)$ and high sheet resistance (kΩ/sq – MΩ/sq) making Hall effect characterization difficult. Instead, we used Hg probe CV measurements to estimate free hole concentration ($p=N_A$), a critical parameter for device design (Fig 1). MOS capacitance structures and Hg probe CV show N_A values ranging over two order of magnitude (10^{17}-10^{19} cm^{-3}) stemming from variations in the oxygen partial pressure. As more oxygen is forced into the NiO, the amount of nickel vacancies (Ni^{3+}); the source of p-type conductivity, increases (Table 1). Other methods of NiO film characterization include ellipsometry and XPS. Ellipsometry is critical for investigating film quality, thickness, and band gap; while XPS has been used to observe the content of the Ni vacancies. We have also investigated ohmic contacts to NiO such as Ni, Pt, and PtOx (Fig. 2, Table 2), all of which produce Schottky contacts to Ga_2O_3. While p-type Ga_2O_3 remains unrealized, continued material research into NiO is critical for the advancement of Ga_2O_3 devices.

Material and Device Processing and Fabrication Techniques
Room Bansal Atrium - Session MD-MoP

Material and Device Processing and Fabrication Techniques Poster Session I

MD-MoP-2 Characteristics of n-ITO/Ti/Au Multilayer for Ohmic Contact on β-Ga_2O_3 Epitaxial Layer, ***Yusup Jung,*** *H. Kim, S. Kim,* Powercubesemi Inc., Republic of Korea*; Y. Jung, D. Chun,* Hyundai Motor Company, Republic of Korea*; T. Kang, S. Kyoung,* Powercubesemi Inc., Republic of Korea

In this paper, The n-ITO/Ti/Au Multilayer for forming an ohmic contact was deposited on the β-Ga_2O_3epitaxial layer by using magnetron sputtering system to apply the source and drain of the lateral β-Ga_2O_3transistor. Multilayer was heated by using Rapid Thermal Annealing (RTA) equipment after deposited multilayer, and the contact resistance, sheet resistance, and linear dependence characteristics were evaluated after measuring the I-V curve using the TLM method. The n-ITO is a transparent conductive material with a band gap of about 3.5eV [1]. It is deposited between β-Ga_2O_3 and Ti metal to improve band alignment between β-$Ga_2O_3$and Ti and to be as an electron injection layer to improve ohmic contact characteristics [2,3]. The n-ITO/Ti/Au Multilayer is deposited on β-Ga_2O_3 epitaxial layer by using DC/RF magnetron sputtering equipment. After deposition process, post annealing process was proceeded within the range of 500 to 800 degrees in a nitrogen gas atmosphere. The I-V characteristics of the fabricated TLM pattern were measured with a keithley 2410. As a result, when the thicknesses of n-ITO, Ti and Au metal were 20nm, 50 nm, and 100 nm, the specific contact resistivity is 1.3 $m\Omega.cm^2$ and exhited strong linear dependence curve at post annealing temperature of 700 degrees.

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[Acknowledgment]

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MD-MoP-3 β-Ga_2O_3 Schottky and Heterojunction Diodes Operating at Temperatures Up to 600°C, ***Kingsley Egbo,*** *S. Schaefer, W. Callahan, B. Tellekamp, A. Zakutayev,* National Renewable Energy Laboratory

Semiconductor device performance and reliability under extreme conditions are essential for several applications in the industrial, energy, and automotive sectors. Wide bandgap oxides such as β-Ga_2O_3 are important materials for high-power device applications and are also well-suited for high-temperature electronics due to reduced temperature-activated parasitic leakage and resistance to oxidation.

Here, we explore the high-temperature operation of Ga_2O_3 based Schottky and *p-n* junction diodes. Vertical heterojunction NiO/*β*-Ga_2O_3 diodes and Ni/*β*-Ga_2O_3 Schottky diodes were fabricated and studied using current-voltage (*I-V*) and capacitance-voltage (*C-V*) measurements in the range of 25 – 600 °C. For the *p-n* diode, a 200nm thick NiO film was grown on a Sn-doped *β*-Ga_2O_3 (100) substrate (≈$2x10^{18}$ cm^{-3}) by pulsed laser deposition, where the (100) substrate face is effective at promoting (100)-textured NiO. After NiO deposition, the device area was mesa isolated by argon dry etching.[1] The Schottky diode was fabricated on a 300 nm unintentionally doped (UID) layer grown on Sn-doped Ga_2O_3 (001) substrates by molecular beam epitaxy (MBE).[2] Schottky diodes were formed by depositing 30 nm Ni / 100 nm Au via e-beam evaporation. For both types of devices, a stable Ohmic back contact to Ga_2O_3 was formed by 5 nm Ti / 100 nm Au annealed under N_2 at 550 °C for 90 seconds.[3]

In the Schottky diode, the turn-on voltage and rectification ratio were found to be 1.2V and 10^8 (±2V), respectively, at room temperature. The rectification ratio decreased strongly with increasing operating temperature to ≈ 10^2 at 600 °C. The temperature dependence of the on-state voltage and increasing leakage current are attributed to barrier inhomogeneity and instability at Ni/*β*-Ga_2O_3 interface and low built-in potential at the Schottky barrier (≈1.0 eV measured by *C-V*). The NiO/*β*-Ga_2O_3 diodes turn-on voltage at RT was found to be 1.9V. Compared to the Schottky diode, a similar rectification ratio of the order of 10^8 was obtained at RT however the rectification ratio only decreased to ≈10^4 at 600 °C. The NiO heterojunction diode also showed lower reverse leakage current up to -10V compared to the Ni-based Schottky diode at high temperatures. These results suggest that while Ga_2O_3 based Schottky barrier diodes hold some potential for high-temperature operation, they are more fundamentally limited by thermally driven leakage current increases. We show that heterojunction *p-n* diodes can significantly improve high-temperature electronic device and sensor performance due to a higher built-in voltage and favorable band offsets.

MD-MoP-4 Structural Properties of Ga_2O_3 Surfaces Treated by Nitrogen Radical Irradiation, ***Kura Nakaoka,*** *S. Taniguchi, T. Kitada, M. Higashiwaki,* Department of Physics and Electronics, Osaka Metropolitan University, Japan

Recently, we found that nitrogen (N) radical irradiation has an effect to significantly restore Ga_2O_3 surface damage and can improve not only Ga_2O_3 Schottky characteristics but also their in-plane uniformity. It can be expected that the nitridation would be one of the key processes for fabrication of various types of Ga_2O_3 devices. In this work, we studied structural properties of nitridated Ga_2O_3 (100) and (010) surfaces to investigate an origin of the improvements in electrical properties.

Surfaces of Ga_2O_3 (100) and (010) substrates were simultaneously nitridated by irradiation of N radicals generated using an RF-plasma cell in a molecular beam epitaxy growth chamber. The process was performed at a substrate temperature of 660℃ for 30, 60, and 120 min. The RF plasma power and N_2 gas flow rate were 500 W and 0.6 sccm, respectively. We observed nitridated Ga_2O_3 surfaces by atomic force microscopy (AFM) and analyzed elemental compositions of the Ga_2O_3 near-surface region using X-ray photoelectron spectroscopy (XPS).

Roughening of the Ga_2O_3 (100) and (010) surfaces occurred by the nitridation process, and the roughness monotonically increased with nitridation time. For the (100) and (010) surfaces, the root-mean-square roughness values were less than 0.2 nm before the N radical irradiation and reached 0.49 and 0.99 nm after the 120-min irradiation, respectively.

Next, we performed XPS analyses for the samples with and without the 120-min N radical irradiation to investigate the progress of nitridation. A clear N 1*s* peak was observed only for the nitridated surfaces, indicating that a large amount of N atoms were successfully incorporated into the Ga_2O_3 by the N radical irradiation. Ga 3*d* peaks of the nitridated surfaces were separated into four gaussian components corresponding to the Ga-O bonding, the Ga-N bonding, the O 2*s* core level, and the N 2*s* core level. The ratios of integrated intensities between the Ga-O and Ga-N peaks, i.e., Ga-N/Ga-O values were 0.51 and 0.74 for the Ga_2O_3 (100) and (010) surfaces, respectively. This result indicates that nitridation more advanced on the (010) surface than the (100) one, which can be attributed to a difference in the density of dangling bonds.

In this study, we investigated structural properties of nitridated Ga_2O_3 (100) and (010) surfaces. Improvements in electrical properties of the Ga_2O_3 Schottky interfaces by N radical treatment are considered due to replacement of a large amount of O atoms by N atoms.

This work was supported in part by the Development Program, “Next-Generation Energy-Saving Devices” of the Ministry of Internal Affairs and Communications, Japan (JPMI00316).

MD-MoP-6 Process Optimization of Sputtered High-K (Sr,Ba,Ca)Tio_3 for Ga_2O_3 Dielectric Layers, ***Bennett Cromer**, C. Gorsak, W. Zhao, L. Li, H. Nair, J. Hwang, B. Van Dover, D. Jena, G. Xing,* Cornell University

β-Ga_2O_3 provides a unique electrostatic challenge due to its large intrinsic breakdown field of 8 MV/cm and moderate dielectric constant of 10. Maintaining oxide fields near 0.5 MV/cm to minimize leakage and degradation thus requires an oxide ε_r of at least 160. Further, high-k dielectrics such as titanates have significant process-property variation which inhibit process integration. Despite pioneer work on Metal/$BaTiO_3$/β-Ga_2O_3 heterojunction diodes[1] and $(BaTiO_3/SrTiO_3)_{15}$ high-k field plates[2], key information such as optimal anneal condition and effective dielectric constant at frequency are yet to be explored. In this work, we use metal-insulator-metal (MIM) and co-planar waveguide (CPW) structures to characterize the complex dielectric constant of $BaTiO_3$, $CaTiO_3$, and $SrTiO_3$ thin films from quasistatic to high frequency. By varying parameters such as deposition and anneal temperatures, we identify a desired process window wherein the dielectric constant is large enough to support intrinsic Ga_2O_3 breakdown with minimal leakage current at application-based operating frequencies.

Thin films of $BaTiO_3$, $CaTiO_3$, and $SrTiO_3$ were deposited by RF magnetron sputtering at 25 °C, 350 °C, and 500 °C on HR-Si as test substrates. Deposition conditions were 50 or 100 W bias for 60 minutes at 5 mTorr with 30 sccm gas flow of 9:1 Ar:O_2. Films were characterized by X-Ray diffraction, spectral reflectance, scanning electron microscopy, and atomic force microscopy pre- and post- anneal to assess crystallinity, surface morphology, and grain size if observable. After annealing, MIM and CPW structures were patterned by standard lithography and deposition of Ti/Au contacts. From these structures complex dielectric constant was extracted from measured impedance. Leakage current was captured from DC IV measurements of the MIM structures. The set of process conditions for each high-k dielectric ($BaTiO_3$, $CaTiO_3$, and $SrTiO_3$) which yielded the most promising leakage and dielectric properties was then replicated on vertical field-plated diode and lateral MOSFET test structures and compared directly to low-k and non-field plated structures.

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.

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MD-MoP-7 Electrical Characteristics of MOCVD Grown β-Ga_2O_3 Schottky Diodes on (010) β-Ga_2O_3 Substrates, ***Sudipto Saha**,* University at Buffalo-SUNY*; L. Meng, D. Yu, A. Bhuiyan,* Ohio State University*; H. Zhao,* ohio State University*; U. Singisetti,* University at Buffalo-SUNY

Monoclinic beta-gallium oxide (Ga_2O_3) is a promising material for power electronics and RF switching due to its ultrawide bandgap. Metal-organic chemical vapor deposition (MOCVD) has emerged as a promising technique for growing high-quality Ga_2O_3 films with smooth surface morphology, controllable doping, and high mobility, making it a preferred method for Ga_2O_3 power devices. However, there are limited reports on the fabrication and characterization of vertical power devices using high growth rate MOCVD-grown Ga_2O_3 films, and the performance of Ga_2O_3 vertical power devices has yet to reach its full potential. Vertical Schottky barrier diodes (SBDs) were fabricated on MOCVD-grown Ga_2O_3 films with varying growth rates, showing promising electrical and structural properties for high-power applications.

In this work, three different Si-doped homoepitaxial Ga_2O_3 films were grown on Sn-doped (010) Ga_2O_3 substrates by MOCVD, labeled S1, S2, and S3. The growth rate for S1 is 3 µm/hr, while S2 and S3 have rates of 650 nm/hr. The epilayer thickness for S1, S2, and S3 are 9.5, 3, and 2 µm, respectively. The S1 sample has the roughest surface of the three samples due to its faster growth rate compared to S2 and S3. The Schottky diodes fabricated with the three samples show excellent rectifying behavior. The diode characteristics such as ideality factor, barrier height, and specific on-resistance show an increase with the growth rate and epilayer thickness, as macro and micro-scale surface roughness also increase.At the same growth rate, the sample with a thicker epilayer exhibits lower forward current density and higher leakage current, which can be attributed to the surface roughness. Notably, though the S3 sample exhibits the highest forward current densities (3386 A/cm^2 at 2.5 V) and lowest specific on-resistance (0.707 mΩ.cm^2), S1 exhibits the lowest leakage currents (8.32×10^{-8} A/cm^2 at -2 V), and highest ON-OFF ratios (>10^9). The capacitance-voltage characteristics showed that all three structures have completely depleted Ga_2O_3 layers on the reverse bias side. The extracted doping density of S1, S2, and S3 are 2.02×10^{16}, 1.73×10^{16}, and 6.08×10^{16} cm^{-3}, respectively.

Overall, the fabricated SBDs exhibit promising electrical and structural properties, with a high current rectification ratio and low reverse leakage current, indicating their potential for high-power applications. The results of our study contribute to the understanding of the growth and characterization of MOCVD-grown Ga_2O_3 films and provide valuable insights for developing high-performance power devices based on this promising material.

Advanced Characterization Techniques
Room Davis Hall 101 - Session AC+MD-TuM

Characterization/Modeling IV

Moderator: Baishakhi Mazumder, University of Buffalo, SUNY

10:45am **AC+MD-TuM-10 Defects in Ga_2O_3: An Ultra-high Resolution Electron Microscopy Study**, ***Nasim Alem***, The Pennsylvania State University; *A. Chmielewski,* CEMES-CNRS, France **INVITED**

Interest in β-Ga_2O_3 has dramatically increased in recent years due to the material's potential promise for use in power electronics and extreme environments. Its combination of a monoclinic structure (C2/m space group), two inequivalent tetrahedral and octahedral gallium sites and three inequivalent oxygen sites, and a bandgap of 4.8 eV, 1.4 eV above that of gallium nitride, creates a semiconductor material with a unique set of properties. This is further aided by β-Ga_2O_3's uncommon capability among the ultra-wide bandgap oxides to be grown into high quality single crystal substrates using both melt-based bulk and thin film growth and deposition methods. Defects and their stability and dynamics under static and extreme environments can limit the incorporation of β-Ga_2O_3 into new applications. Therefore, a direct visualization and in-depth understanding of the defects and their interplay with the environment is vital for understanding the materials properties and the device breakdown under extreme conditions. In this presentation we will discuss the atomic, electronic, and chemical structure of the defects in doped and UID β-Ga_2O_3 using scanning transmission electron microscopy (S/TEM) imaging and electron energy loss spectroscopy (EELS). In addition, we will discuss the electronic structure and the local properties in β-Ga_2O_3 under extreme conditions using STEM-EELS. This fundamental understanding is important to uncover the breakdown behavior in β-Ga_2O_3 and the impact of defects on its device performance.

11:15am **AC+MD-TuM-12 Sub-oxide Ga to Enhance Growth Rate of β-Ga_2O_3 by Plasma-assisted Molecular Beam Epitaxy**, ***Zhuoqun Wen***, *K. Khan, E. Ahmadi,* University of Michigan, Ann Arbor

In recent years, there has been significant interest in β-Ga_2O_3 as a potential candidate for the next generation of power electronics, solar-blind ultraviolet (UV) detectors, and as a substrate for UV light emitting diodes (LEDs). This interest stems from its ultra-wide bandgap of 4.8eV. Thin film growth and n-type doping (Si, Sn, Ge) of Ga_2O_3 have been achieved through various methods such as metal-organic chemical vapor deposition (MOCVD), pulsed laser deposition (PLD), and molecular beam epitaxy (MBE). However, MBE has limitations in terms of the growth rate of Ga_2O_3 due to the desorption of volatile Ga_2O, which is formed from the reaction between Ga and Ga_2O_3. Using gallium sub-oxide (Ga_2O) instead of elemental gallium has been previously employed [1] as a technique to enhance the growth rate of Ga_2O_3 by Ozone-MBE. However, this technique has not yet been investigated in plasma-assisted MBE. In my talk, I will present the results of our recent studies on using Ga_2O as Ga source in PAMBE. Using the same plasma conditions, we show that using Ga_2O instead of Ga can at least double the growth rate of Ga_2O_3.

Previously, we have demonstrated uniform and controllable silicon doping of β-Ga_2O_3 by utilizing disilane (Si_2H_6) as the Si source. [2] In my talk, I will show that this technique is also compatible with utilizing Ga_2O as Ga source. The silicon doping can be tuned from 3×10^{16} cm^{-3} to 1×10^{19} cm^{-3} using the diluted disilane source.

References:

1. Vogt, P., Hensling, F. V., Azizie, K., Chang, C. S., Turner, D., Park, J., ... & Schlom, D. G. (2021). Adsorption-controlled growth of Ga_2O_3 by suboxide molecular-beam epitaxy. *Apl Materials*, *9*(3), 031101.

2. Wen, Z., Khan, K., Zhai, X., & Ahmadi, E. (2023). Si doping of β-Ga_2O_3 by disilane via hybrid plasma-assisted molecular beam epitaxy. *Applied Physics Letters*, *122*(8)

11:30am **AC+MD-TuM-13 Microscopic-Scale Defect Analysis on Ga_2O_3 through Microscopy**, *M. Kim,* NIST-Gaithersburg, Republic of Korea; *A. Winchester, O. Maimon,* NIST-Gaithersburg; *S. Koo,* KwangWoon University, Korea; *Q. Li,* George Mason University; ***Sujitra Pookpanratana***, NIST-Gaithersburg

Crystalline defects of technologically mature materials have been identified and classified by the semiconductor industry [1,2], since it is economically beneficial to isolate failure mechanisms at the source rather than relying on backend testing. This has significantly improved device reliability. The various defects could be categorized into killer or non-killer defects, where killer defects can hinder the operation of high-performance devices by trapping charge carriers or causing increased leakage current. Although β-gallium oxide (β-Ga_2O_3) is expected to surpass silicon carbide (SiC), defects in Ga_2O_3 are prevalent and largely unclassified. Therefore, screening out defects that cause electrical device degradation must be solved for widespread adoption of β-Ga_2O_3.

In this work, photoemission electron microscopy (PEEM) is used to visualize micrometer-scale defects and determine their electronic impact. PEEM is based on the photoelectric effect and is a non-destructive analysis method where light is used to excite and eject electrons from the sample surface and these electrons are analyzed. We investigated the defects on commercially-available epitaxially-grown β-Ga_2O_3 on (010) β-Ga_2O_3 substrates. The epitaxy was formed by hydride vapor phase epitaxy (HVPE) with a target doping of $1x10^{18}$ cm^{-3} on the (010) semi-insulating β-Ga_2O_3 wafer. We identified elongated structures on the β-Ga_2O_3 epi-layer as shown in Figure 1a, and they appear in multiple instances of the sample surface and in a parallel configuration. These features resemble the "carrot" defect observed in SiC epitaxy [3]. From the imaging spectroscopy mode of the PEEM (Figure 1b), the base and tip of the carrot were found to have similar valence band maxima but dissimilar work functions. The spectra from the tip of the carrot resembles that of the surrounding β-Ga_2O_3 epi-layer. We are performing ongoing work to identify this feature as a microscopic defect. For understanding the electrical influence of these elongated features on HVPE epi-layer, we will perform tunneling atomic force microscopy (TUNA) to measure the electrical properties on and off the defect surface. Together, we will present a discussion on the nature of these distinct features and their implication on device performance.

11:45am **AC+MD-TuM-14 Characterization and Processing Improvements for Fabricating and Polishing β-Ga2O3 Substrates**, ***Robert Lavelle***, *D. Snyder, W. Everson, D. Erdely, L. Lyle, N. Alem, A. Balog,* Penn State University; *N. Mahadik, M. Liao,* Naval Research Laboratory

As progress continues to be made in fabricating and polishing uniform, high-quality β-Ga2O3 substrates, it is increasingly important to link commercial suppliers and research groups with expertise in crystal growth, substrate processing, epi growth/synthesis, characterization, and devices. This creates a vertically integrated feedback loop that drives answering fundamental research questions and increasing the manufacturability of the substrates. We will review our latest results in optimizing the chemi-mechanical polishing (CMP) methods and related processing steps for β-Ga2O3 substrates and materials characterization. This includes quantifying and minimizing subsurface damage related to processing, investigating the propagation of defects such as nanopipes, fabricating off-cut/off-axis substrates, and extending the fabrication/polishing methods to different alloy compositions.

Previous results showed that an excellent surface finish (Ra <2 Å over a >0.175 mm2 area) could be achieved for Czochralski (Cz) grown β-Ga2O3 substrates using a two-step CMP process with a nearly 10X reduction in polishing cycle time. After continuing to develop this process, we observed that a similar surface finish could be achieved by optimizing the pH of the colloidal silica slurry while realizing a further 3-4X reduction in cycle time. This establishes a path toward a milestone 1-day polishing process for β-Ga2O3 substrates. While the surface finish is similar, further reduction in the FWHM of the x-ray rocking curves (XRRCs) was also obtained by reducing the force and optimizing the other polishing parameters during the final CMP step. These processing changes suggest improvement in polishing related subsurface damage, which we assessed using high-resolution x-ray diffraction (HRXRD) by varying the x-ray penetration depth and advanced microscopy techniques.

Uniformity continues to be an important consideration as commercial 2"+ substrates become increasingly available. We continue to map and collect characterization data from across substrates grown by Cz and edge-defined film-fed growth (EFG) and will share our observations. This includes site-specific XRRC measurements as well as etch pit density (EPD) mapping and defect analysis for full substrates. In this discussion, we will also integrate feedback from epi growers for different types of substrates. Finally, we will discuss our methodology for processing off-cut/off-axis as well as alloyed substrates and latest characterization results.

Keynote Address
Room Davis Hall 101 - Session KEY-TuM

Keynote Address II

Moderators: Uttam Singisetti, University of Buffalo, SUNY, **Joel Varley**, Lawrence Livermore National Laboratory

8:30am **KEY-TuM-1 Welcome and Opening Remarks***,*

8:45am **KEY-TuM-2 Bulk Single Crystals and Physical Properties of β-$(Al_xGa_{1-x})_2O_3$ Grown by the Czochralski Method***, Zbigniew Galazka,* LEIBNIZ-INSTITUT FÜR KRISTALLZÜCHTUNG, Germany **INVITED**

β-Ga_2O_3 is a transparent semiconducting oxide that attracted a particular attention in the research community with potential applications especially in high power electronics and UV opto-electronics. This is the result of a wide bandgap of 4.85 eV, good electrical properties enabling a wide doping range, high theoretical breakdown field of 8 MV/cm, and a capability of growing large bulk single crystals and thin films of high structural quality [1].

A yet higher critical breakdown field of β-Ga_2O_3 can be achieved by enlarging its bandgap through heavy doping with Al. For homoepitaxial growth of β-$(Al_xGa_{1-x})_2O_3$ films and subsequent device fabrication, wafers from bulk single crystals of similar composition would be highly beneficial. We have already demonstrated the capability of growing bulk β-$(Al_xGa_{1-x})_2O_3$ single crystals by the Czochralski method with x = 0 – 0.35, and provided basic structural, optical, and electrical properties [2].

The present study provides an overview of the growth of bulk β-$(Al_xGa_{1-x})_2O_3$ single crystals by the Czochralski method, including thermodynamics and limits of Al incorporation in the monoclinic β-Ga_2O_3 crystal lattice, as well as limits of Ga incorporation in the trigonal a-Al_2O_3 crystal lattice. In addition to Al doping, the crystals were co-doped either with Si or Mg. The study is accompanied with extended characterization of physical properties of β-$(Al_xGa_{1-x})_2O_3$ as a function of [Al]. It covers structural (lattice constants), electrical (free electron concentration, electron mobility, BOFM), optical (absorption edge, bandgap, static dielectric constants, refractive index), and thermal (thermal conductivity) properties. A high doping level of bulk β-Ga_2O_3 single crystals with [Al] ≤ 35 mol.%, their high structural quality, and a wide spectrum of physical properties might facilitate homoepitaxial growth of β-$(Al_xGa_{1-x})_2O_3$ films and novel device fabrication.

This work was funded by the Deutsche Forschungsgemeinschaft (DFG) project under Grant Nos. GA 2057/5-1 and PO 2659/3-1. It was partly performed in the framework of GraFOx, a Leibniz-Science Campus, partially funded by the Leibniz Association—Germany.

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Theory, Modeling and Simulation
Room Davis Hall 101 - Session TM-TuM

Characterization/Modeling III

Moderators: Uttam Singisetti, University of Buffalo, SUNY, **Joel Varley**, Lawrence Livermore National Laboratory

9:15am **TM-TuM-4 Electron–Phonon Effects and Temperature-Dependence of the Electronic Structure of Monoclinic *β*-Ga_2O_3 from First Principles***, Elif Ertekin,*** *C. Lee,* University of Illinois at Urbana-Champaign, USA*; M. Scarpulla, N. Rock, A. Islam,* University of Utah **INVITED**

A primary reason that *β*-Ga_2O_3 is a promising semiconductor for next-generation high-power electronics is its ultra-wide band gap, resulting in desirable high critical breakdown field. While first-principles approaches have provided key insights into the ground state electronic structure of *β*-Ga_2O_3, temperature-dependent properties however have remained challenging to model. Yet, they are important: temperature effects underlie key semiconductor properties such as carrier mobility, band edge positions, and optical absorption. To utilize the unique electrical properties of *β*-Ga_2O_3 for real-world applications, an accurate description of electronic structure under device-operating conditions is required. In this presentation, I will highlight our recent progress in modeling key temperature-dependent aspects of the electronic structure of *β*-Ga_2O_3 -- namely, how electron-phonon coupling affects the band structure and band gap. Utilizing the quasi-harmonic approximation and the recently developed "one-shot" frozen phonon method, we have been able to predict the temperature-dependent electronic band structure of *β*-Ga_2O_3 in a wide temperature range from T = 0 to 900 K using first-principles simulations. Band edge shifts from lattice thermal expansion and phonon-induced lattice vibrations known as electron–phonon renormalization together are found to induce a substantial temperature-dependence on the band gap, with the latter giving the dominant contribution. We find that the band gap is reduced by more than 0.5 eV between T = 0 and 900 K. Our prediction of temperature-dependent band gap matches well with previously reported and our new experimental optical measurements, further emphasizing the need for accounting for such effects in first-principles simulations of wide band gap semiconductors. As the temperature dependence and the band gap reduction is quite a bit larger than that observed in other wide band gap materials, key implications for device performance will be discussed. These implications include an increase in carrier concentrations, a reduction in carrier mobilities due to localization of band edge states, and a ∼20% reduction in the critical breakdown field at 900 K. Future directions for analysis -- including challenges in modeling thermal-disorder induced Urbach effects and breakdown -- will be discussed as well.

9:45am **TM-TuM-6 Ab-Initio Calculation of Low Field Electron Transport in Disordered Bulk β-$(Al_xGa_{1-x})_2O_3$ Semiconductor Alloy***, Ankit Sharma, U. Singisetti,* University at Buffalo-SUNY

β-Ga_2O_3 is an emerging UWBG semiconductor with potential applications in power and RF devices due to its large bandgap, high critical electric field and low on-resistance. The availability of bulk substrates with a matured crystal growth methodology makes it a strong contender to SiC and GaN, the two widely used materials for power and RF applications. With all is benefits, overcoming the low bulk electron mobility due to large polar scattering is a major challenge in this material. As such the Ga_2O_3 device research has pivoted to using AlGaO/GaO heterostructures to harness the high electron mobility of the 2DEG formed at the interface as a result of the band offset. Many devices employing this heterostructure have already been successfully demonstrated. In order to improve and optimize performance of the devices, the fundamental understanding of the charge transport mechanism lies at the crux. Extensive theoretical and experimental investigations have been performed for the bulk GaO, but for the AlGaO alloy the results are scarce. This is further complicated by the fact that with aluminum substitution the translational symmetry in the crystal is lost which forms the basis for the theoretical modeling of the charge transport mechanism. In this work, we extend the periodic crystal based formulation of the electron and phonon dispersion to this disordered system through the Brillouin zone unfolding method where the disorder is modeled using supercell special quasirandom structures. The analysis is further extended to calculate the shortrange deformation potential, longrange polar optical, ionized impurity and alloy disorder scattering from first principles. The Boltzmann transport equation (BTE) is subsequently solved under the Rode's iterative framework to obtain electron mobility. The currently available results for AlGaO alloy solve the BTE for periodic structures and then interpolate the result at intermediate alloy fractions using Vegard's law. Our application of the ab-initio approach at intermediate alloy fractions is novel and eliminates the need for interpolation along with providing insight into the mobility limiting scattering mechanisms under low applied electric fields. We also propose a method to calculate the IR spectra of disordered systems such that theoretical and experimental observation could be compared directly. Some of the results obtained as the part of our initial work in the calculation of the electron mobility in the AlGaO disordered system from first principles is presented in the supplementary material.

10:00am **TM-TuM-7 Quantitative Modelling of Defect Concentrations in β-Ga_2O_3 for Equilibrium, Full Quenching, and Generalized Quenching Scenarios**, ***Khandakar Aaditta Arnab**, I. Maxfield,* University of Utah*; C. Lee, E. Ertekin,* University of Illinois at Urbana Champaign*; J. Varley,* Lawrence Livermore National Laboratory*; Y. Frodason,* University of Oslo, Norway*; M. Scarpulla,* University of Utah

β-gallium oxide (β-Ga_2O_3) is of intense current interest because of its ultra-wide bandgap, high critical field, and availability of melt-grown substrates. Point defects and complexes determine the properties of bulk crystals as well as epitaxial layers, thus, predictive models of defect concentrations under various impurity and processing scenarios are of very high value. First-principle calculations of defect energetics have provided critical insights into the defect system in β-Ga_2O_3, but translating computed enthalpies into defect concentrations corresponding to real-world crystal growth requires additional steps. Material processing in terms of growth or annealing typically controls the sample's thermochemical trajectory in terms of temperatures and partial pressures, while computational papers frequently present results holding chemical potentials constant.

Here we report quantitative modelling of equilibrium defect concentrations in Ga_2O_3, considering especially the temperature dependence of the bandgap and temperature-dependent chemical potentials from the Ga-O binary system's known thermochemistry. Additionally, we compute results for realistic sample types such as Fe- or Sn-doped wafers accounting for the fixed concentrations of these impurities as opposed to their fixed chemical potentials. Results are presented for various background n-type doping and for equilibrium and quenching, corresponding respectively to 0 or infinite cooling rates. We find significant departures from prior simpler predictions, especially in the case of the bandgap temperature dependence which tends to suppress V_{Ga}. We compare our predicted results to experimental cases such as annealing in O_2 or Ga_2O vapors.

Finally, to give semi-quantitative insight into defect concentrations expected in finite-sized samples subjected to finite cooling rates without full-fledged defect reaction-diffusion simulations, we introduce the concept of generalized quenching as a 3rd type of computation. At the heart of generalized quenching is the insight that, because of their different diffusion constants, different types of defects located at different distances from free surfaces will be "frozen-in" at different temperatures. By combining the correct series of equilibrium and quenching calculations, it is possible to predict defect concentrations present in real-world samples e.g. as a function of radius within a boule or for thin films of different thicknesses. We compare these results to the known phenomena from bulk crystal growth, indicating differences in carrier density between the center and periphery of CZ-grown boules.

10:15am **TM-TuM-8 Exploring Gallium Oxide (β-Ga_2O_3) Drift Layer Design: Theoretical Analysis and Trade-offs**, ***Sundar Isukapati**, S. DeBoer, S. Jang,* SUNY Polytechnic Institute, Albany*; Y. Jung,* Hyundai Motor Company, Republic of Korea*; W. Sung,* SUNY Polytechnic Institute, Albany

Gallium Oxide (Ga_2O_3) has emerged as a highly promising material for power devices due to its wider bandgap and high critical electric field. In this paper, we investigate the drift layer design for Ga_2O_3 power devices through theoretical analysis and trade-offs. The drift layer, similar to other wide-bandgap materials, plays a crucial role in the performance of Ga_2O_3 power semiconductor devices. The two primary drift layer configurations, non-punch through (NPT) and punch-through (PT), are analyzed with a focus on key design parameters such as drift layer thickness (W_D) and doping concentration (N_D), and their impact on specific on-resistance ($R_{on,sp}$) for both NPT and PT structures. Furthermore, we extend the specific on-resistance to breakdown voltage (BV) trade-off analysis by considering the additional resistance components for both lateral and vertical MOSFETs, providing a practical guide for device researchers to pursue the appropriate architectures based on the voltage rating.

The ionization rate of the electrons in Ga_2O_3 shown in Fig. 1, is utilized for the evaluations. The electric field at the onset of BV (referred to as the critical electric field, E_c) is extracted iteratively by solving the ionization integral with the ionization rates for both non-punch through (NPT) and punch-through (PT) structures. The critical electric field exhibits a strong dependence on the doping concentration for both non-punch through (NPT) and punch-through (PT) structures (with varying widths) as illustrated in Fig. 2. The impact of doping concentration and width on the BV for both NPT and PT structures (with varying widths) is depicted in Fig. 3. The ionization ratio as a function of doping concentration is extracted from the ionization energies of donors is shown in Fig. 4. With reduced doping concentration and width, the optimal $R_{on,sp}$ of the punch-through (PT) structure is about 8% lower than that of the non-punch through (NPT) structure at a particular BV, as depicted in Fig. 5. To further explore the trade-off analysis, a Ga_2O_3 MOSFET with both lateral and vertical architectures was considered. Using reasonable assumptions and practical specifications, the channel, drift, and substrate resistances were evaluated. Fig. 6 depicts the individual and total resistance components associated with lateral devices (channel and drift resistances represented by red curves) and vertical devices (channel, drift, and substrate resistances represented by blue curves). It is evident from Fig. 6 that, at breakdown voltages lower than ~2kV, the lateral device offers the lowest possible $R_{on,sp}$ but beyond ~2kV, the vertical device dominates by offering a lower $R_{on,sp}$.

Epitaxial Growth
Room Davis Hall 101 - Session EG+BG-TuA

Bulk/Epitaxy II

Moderator: Sriram Krishnamoorthy, University of California Santa Barbara

1:45pm **EG+BG-TuA-1 Suitable Orientation for Homoepitaxial Growth of Gallium Oxide**, ***Kohei Sasaki,*** *A. Kuramata,* Novel Crystal Technology, Inc., Japan **INVITED**

The surface orientation is an important condition in homoepitaxial growth. β-Ga_2O_3 has an unusual crystal structure, named β-Gallia, so we cannot use the knowledge of the usual crystal structures, such as diamond, zinc blende or wurtzite, when the selecting the surface orientation. Here, we investigated suitable orientations for homoepitaxial growth of gallium oxide by growing films on gallium oxide substrates with various orientations.

The β-Gallia structure is monoclinic, and its low index planes are (100), (010), and (001). We made gallium oxide substrate with surface orientations from the (100) to (010) plane or from the (100) to (001) plane and investigated the crystal quality, surface roughness, and growth rate of the films grown by molecular beam epitaxy. We sliced the surface in ten degrees steps from the (100) plane rather than adjusting the specific orientation. Growth temperature was fixed at 700 degrees Celsius. Ozone gas was used as the oxygen source.

Of the planes between the (100) and (010) plane, only the (100) plane showed a peculiarly low growth rate. On the other hand, there were no unusual features on the planes except the (100) plane; the growth rate was about 700 nm/h, and surface roughness (RMS) was about 1-2 nm.

On the other hand, the planes between the (100) and (001) plane showed severe surface roughness especially around the (101) plane and (-201) plane. The surface roughness on the (101) plane was due to crystal defects in which (-201) crystal grew on the (101) plane, whereas on the (-201) plane it was due to (-201) twin defects. We obtained very smooth surfaces with an RMS of 1 nm or less by using the (001), (-102), (401), (-401) planes.

It is known that the surface orientation of gallium oxide homoepitaxial growth depends on the growth method. The surfaces of films grown by MBE and metalorganic chemical vapor deposition (MOCVD) show similar morphologies. Thus, the knowledge gained in this research may be applicable to MOCVD.

2:15pm **EG+BG-TuA-3 Pushing the Al composition limit up to 99% in MOCVD β-$(Al_xGa_{1-x})_2O_3$ films using TMGa as Ga precursor**, ***A F M Anhar Uddin Bhuiyan,*** *L. Meng, H. Huang, J. Hwang, H. Zhao,* The Ohio State University

Recent research progresses have highlighted the promising potential of the MOCVD growth method in developing β-$(Al_xGa_{1-x})_2O_3$ alloys along different crystal orientations with high Al composition and controllable n-type doping. The coexistence of β and γ phases in (010) β-AlGaO films with Al>27% indicates challenges for incorporating higher Al compositions. Using alternative crystal planes of β-Ga_2O_3 substrates, such as (100) and (-201), has yielded single phase β-AlGaO films, with over 50% of Al incorporation. These prior efforts on MOCVD growth of β-AlGaO alloys using TEGa as the Ga precursor limit the film growth rate to below ~0.7 µm/hr.

In this study, we employed TMGa as the Ga precursor, which not only elevates the growth rates of β-AlGaO films up to 2 µm/hr, but also enhances the Al compositions up to a record high value of ~99%. The systematic investigation of MOCVD growth of β-AlGaO films and β-AlGaO/Ga_2O_3 superlattices on different crystal planes revealed a strong impact of substrate orientation on the solubility limit of β-AlGaO grown at relatively high growth rates. The crystalline structure, strain, morphology, stoichiometry, and bandgap of β-AlGaO films are investigated as a function of the Al composition and crystal orientations. β-AlGaO films with Al compositions up to 99%, 29%, 16% are achieved on (100), (010) and (-201) β-Ga_2O_3 substrates, respectively, as determined by XRD, XPS and STEM EDX. Beyond 29% of Al incorporation, the (010) β-AlGaO films exhibit β to γ phase transformation. Owing to its highly anisotropic characteristics, (-201) β-AlGaO films show local segregation of Al. Fully strained coherent β-AlGaO films are obtained for thicknesses of 350 nm (010, Al=15%), 120 nm (100, Al=16%) and 205 nm (-201, Al=13%). The crystalline structure of 20 nm thick β-$(Al_{0.99}Ga_{0.01})_2O_3$ film was accessed by atomic resolution STEM imaging, showing sharp interface and alloy homogeneity. The electron nano-diffraction pattern and quantitative STEM-EDX elemental mapping confirm the β-phase growth with Al composition of 99%, which agrees well with XRD and XPS measurement results. A record high bandgap energy of 7.26 eV is achieved from β-$(Al_{0.99}Ga_{0.01})_2O_3$ film using XPS, revealing great promises of developing β-AlGaO/Ga_2O_3 interfaces with high band offsets. The findings of this study offer valuable insights on the MOCVD epitaxy and properties of high Al composition β-AlGaO films and β-AlGaO/Ga_2O_3 heterostructures for device applications.

Acknowledgment: AFOSR (FA9550-18-1-0479) and NSF (Grant No. 2231026, and 2019753).

2:30pm **EG+BG-TuA-4 Fast Growth and Characterization of Undoped β-Ga_2O_3 on 2-Inch Substrates Using a Horizontal Hot-Wall MOVPE System**, ***Kazutada Ikenaga,*** Tokyo University of Agriculture and Technology / TAIYO NIPPON SANSO CORPORATION, Japan*; J. Yoshinaga, P. Guanxi,* TAIYO NIPPON SANSO CORPORATION, Japan*; H. Tozato, T. Okuyama, K. Goto, Y. Kumagai,* Tokyo University of Agriculture and Technology, Japan

Metalorganic vapor phase epitaxy (MOVPE) is one of the attractive methods for the epitaxial growth of β-Ga_2O_3. However, it requires control of the hazardous reactions between organometallics and oxygen (O_2) while suppressing the incorporation of carbon (C) and hydrogen (H) impurities derived from the organometallics. Our research group has clarified the key conditions that enable the growth of high-purity β-Ga_2O_3 layers with suppressed C and H incorporation by thermodynamic analysis and in situ mass spectrometry of gaseous species in the reactor [1-3]. In this work, we report on the uniform and fast growth of β-Ga_2O_3 on 2-inch substrates.

A horizontal low-pressure hot-wall MOVPE system (TAIYO NIPPON SANSO CORPORATION, FR2000-OX) with a facedown holder capable of placing 2-inch diameter substrates was used. One 2-inch diameter c-plane sapphire wafer or three 10 mm × 15 mm sized β-Ga_2O_3(010) substrates were set for each growth. Epitaxial layers were grown in a temperature range of 900–1050 °C using trimethylgallium (TMGa) and O_2 as precursors, and Ar as a carrier gas, respectively. Under a constant O_2 supply, TMGa was supplied in the range of 111 – 546 µmol/min (corresponding to the input VI/III ratio from 1609 to 327).

The growth rate was found to be constant regardless of the growth temperature. At a growth temperature of 1000°C, the growth rate increased linearly up to about 15 µm/h with increasing TMGa supply rate, while the C impurity concentration increased. Since an increase in H and C impurity concentrations was observed with decreasing growth temperature, it is likely that the increase in these impurities is due to the increase in TMGa-derived hydrocarbons and their insufficient combustion. It was also found that there is no difference in growth rate between heteroepitaxial growth and homoepitaxial growth under the same conditions. In this presentation, the uniformity of the grown layer is also reported.

This work was supported by Ministry of Internal Affairs and Communications (MIC) research and development (JPMI00316).

[1] K. Goto et al., Jpn. J. Appl. Phys. **60**, 045505 (2021).

[2] K. Ikenaga et al., J. Cryst. Growth **582**, 126520 (2022).

[3] K. Ikenaga et al., Jpn. J. Appl. Phys., in press.

2:45pm **EG+BG-TuA-5 MBE Growth and Properties of Ultra-wide Bandgap Oxide Layers Spanning 5.0 - 9.0 eV Energy Gaps**, ***Debdeep Jena,*** Cornell University **INVITED**

3:15pm **EG+BG-TuA-7 Structural Defect Formation and Propagation in Fe-doped Czochralski-grown b-Ga_2O_3 Boules**, ***Luke Lyle,*** Pennsylvania State University - Applied Research Lab*; R. Lavelle,* Penn State University - Applied Research Lab*; D. Erdely,* Pennsylvania State University - Applied Research Lab*; W. Everson,* Penn State University - Applied Research Lab*; A. Balog, N. Alem,* Pennsylvania State University*; D. Snyder,* Pennsylvania State University - Applied Research Lab

Over the last decade, β-Ga_2O_3 has garnered increased attention due to its ultrawide bandgap of 4.7-4.9 eV, controllable range of shallow, n-type dopants (Sn, Si, Ge), and easily scalable and economic melt growth processes. Popular melt-growth processes that have been developed for β-Ga_2O_3 include the edge-defined film fed method, vertical bridgeman, and the Czochralski process. Although different types of structural defects in these melt-grown crystals have been identified, how they form and propagate throughout the growth process remains elusive. Specifically, it has been found that the density of structural defects can vary across wafers in the same boule and even across a single wafer.

We etch and analyze double side, chemi-mechanically polished 2” diameter wafers and 1” diameter wafers taken from ‘cores’ from 2” diameter boules at the tip, center, and tail of Fe-doped (010) Czochralski-grown boules. The etch pits were formed using an optimized H_2PO_4 etch process and are

mapped using automated optical microscopy, statistical analysis software and scanning electron microscopy and are organized by defect type and density across each wafer analyzed in the boule. Wafers from the length of the boule were used to assess seeding and growth initiation related defect structures and long-range propagation and results from adjacent wafers at various locations were studied to understand short range defect formation and propagation. Trends regarding the presence of dislocations/nanopipes and their formation throughout the boule are discussed along with differentiation between process- and growth-related defects. Particular attention in this talk is paid to the formation and propagation of so-called "nanopipe" defects, as they are poised to act as killer-defects for high-voltage devices

Material and Device Processing and Fabrication Techniques
Room Davis Hall 101 - Session MD+AC+EP-TuA

Process/Devices II

Moderator: Yuhao Zhang, Virginia Tech

3:45pm **MD+AC+EP-TuA-9 Large Area Trench β-Ga_2O_3 Schottky Barrier Diode with Extreme-K Dielectric Resurf**, ***Saurav Roy,*** *A. Bhattacharyya,* University of California Santa Barbara*; J. Cooke,* University of Utah*; C. Peterson,* University of California Santa Barbara*; B. Rodriguez,* University of Utah*; S. Krishnamoorthy,* University of California Santa Barbara

We report the first combination of high-k dielectric RESURF with trench geometry to realize low reverse leakage large area (1mm^2 and 4mm^2) β-Ga_2O_3 Schottky Barrier Diodes with high current values (15A pulsed, 9A DC). 1.2 µm deep trenches are etched on HVPE-grown 11 µm epilayer with 8×10^{15} cm^{-3} apparent charge density concentration using dry etching and 300 nm $BaTiO_3$. (BTO)is then sputter deposited which is followed by annealing at 700°C to enhance the dielectric constant. The fins are then opened using dry etching. Pt/Au Schottky contacts are deposited using e-beam evaporation with planetary rotation for conformal deposition. To further improve the breakdown voltage field plates are used with Si_3N_4 as the field plate oxide. A planar SBD, a BTO field-plated SBD, and a trench SBD with high-k RESURF are fabricated for comparison. The on resistance ($R_{on,sp}$ normalized to the device footprint) of the planar and field plated SBDs are extracted to be 7.9 and 8.2 mΩ-cm^2, respectively, and an increased on resistance of 10.8 mΩ-cm^{-2} is measured for small area (200×200 μm^2) trench SBD with high-k RESURF, indicating dry etching induced damage. The breakdown voltage of the BTO field-plated SBD increases to 2.1 kV from 816 V (planar SBD) whereas the breakdown voltage increases to 2.8-3kV for the trench SBD with high-k RESURF. A very low leakage current density of 2×10^{-4} A/cm^2 is measured for the trench SBD at 2.8 kV. The 1 mm^2 trench SBD exhibits a current of 3.7A(Pulsed)/2.9A(DC) and the 4mm^2 trench SBD exhibitsa current of 15A(Pulsed)/9A(DC) at 5V. The breakdown (catastrophic) voltage of the 1mm^2 and 4mm^2 trench SBDs are measured to be 1.4 and 1.8kV. The leakage currents at breakdown are significantly lower compared to other high current SBDs reported in the literature despite the large area of the device, due to the much-reduced parallel field at the metal/semiconductor interface. Temperature dependence of on resistance shows lower temperature co-efficient (α = 0.87) which is lower than SiC SBDs. The large area high-k RESURF trench SBDs also has lowest $V_{on}I_{leakage}$ product for any β-Ga_2O_3 SBDs with more than 1kV breakdown voltage and 1A current, which is important to reduce both the on and off-state power dissipation. The 4mm^2 high-k RESURF trench SBD has the highest current (5A(DC)/9A(Pulsed)) at V_F = V_{on}+2V with breakdown voltage more than 1.3kV and exhibits lowest leakage current for similar rated device from literature.

This material is based upon work supported by the II-VI Block Gift Program and the Air Force Office of Scientific Research MURI award FA9550-21-0078.

4:00pm **MD+AC+EP-TuA-10 Fabrication and Characteristics of Ga_2O_3 MOSFET using p-NiO for Normally-off Operation**, ***Daehwan Chun,*** *Y. Jung, J. Park, J. Hong, N. Joo, T. Kim,* Hyundai Motor Company, Republic of Korea

In order to increase sales of electric vehicles, it is essential to have market competitiveness by reducing price and improving performance, as well as improving mileage. To increase the mileage of an electric vehicle, it is important to efficiently use the limited power of the battery. The inverter/converter/OBC plays a role in converting electrical energy into a form suitable for electrical components, and the power semiconductor performs switching and rectification operations in the components responsible for such power conversion. Therefore, the performance of power semiconductors is directly related to the mileage of electric vehicles.

Existing power semiconductors mainly used Silicon(Si) materials, but recently, Silicon Carbide(SiC) power semiconductors with improved performance have been mass-produced and started to be installed in vehicles. Gallium Oxide(Ga_2O_3), which has a wider energy bandgap(4.7~4.9eV) than SiC, has a high critical electric field, excellent electron transport ability, and high-quality large-area substrate growth, so it has the advantage of not only performance compared to existing GaN or SiC semiconductor but also easy manufacturing process. In particular, the unit price of Ga_2O_3 epitaxial wafer is expected to be reduced to 1/3 of that of SiC. Therefore, the manufacturing cost is also expected to be lower than that of SiC power semiconductors.

In this paper, we present the fabrication results of Ga_2O_3-based lateral MOSFETs for inverter/converter/OBC applications of electric vehicles. Normally-off operation was secured through the application of NiO, which does not require an ion implantation process, and a breakdown voltage of 600V was achieved. In addition, Al_2O_3 was used as a gate insulating film to suppress gate leakage current, and high-concentration ITO was applied to form an ohmic junction.

Applying NiO to form the depletion layer in the channel region when the MOSFET is off-state ensures normally-off operation of the Ga_2O_3 MOSFET. However, there is a limit to gate voltage application due to leakage current because of the existence of a pn heterojunction diode in the gate region. To solve this problem, an insulating film(Al_2O_3) was formed between NiO and the gate metal. The threshold voltage of the MOSFET with this structure formed a high value of 30V or more, so the threshold voltage was lowered by modifying the concentration of the Ga_2O_3 epitaxial layer. As a result, some drain-source leakage current occurred, but an IV characteristic graph that clearly distinguishes the On/Off state of the MOSFET was obtained.

4:15pm **MD+AC+EP-TuA-11 On the Mg-Diffused Current Blocking Layer for Ga_2O_3 Vertical Diffused Barrier Field-Effect-Transistor (VDBFET)**, ***Ke Zeng,*** *Z. Bian, S. Chowdhury,* Stanford University

To truly realize the potential of the Ga_2O_3 in a transistor, it is imperative to design a buried gate barrier junction to circumvent the pre-mature breakdown near the gate often seen in lateral structures. Owing to the high diffusivity of dopants and defects in Ga_2O_3, in contrast to that of, for example, SiC at a moderate temperature, we propose the use of diffusion doping as a rapid and non-invasive platform to explore the possibility of an effective current blocking layer (CBL) in vertical Ga_2O_3 transistors. In this work, we will discuss the development and characteristics of the Mg diffused CBL that was recently utilized to demonstrate an efficient Ga_2O_3 VDBFET with remarkable pinch-off characteristics.

The process (Fig. 1) starts with a commercially available Ga_2O_3 HVPE epitaxial wafer. The wafer was first coated with a highly Mg-doped spin-on-glass (SOG) layer which was subsequently cured and then patterned by HF to form the selective Mg dopant source. A thick PECVD layer was deposited onto the sample to isolate and stabilize the diffusion doping process. The Mg was then diffused into the wafer under a 950 ℃ furnace annealing for ~1 hr to form the CBL. The dopant oxide stack was stripped clean by an HF dip afterward. A Ni/Au anode was then deposited on top of the CBL region for the 2-terminal CV and IV studies shown in Fig. 2. Furthermore, for the 3-terminal VDBFET, a high dose titled Si triple ion implantation was done to form the source contact region inside the CBL area, followed by an activation annealing. The Ti/Au and Ni/Au composite source electrode was deposited on top of the source and CBL region respectively. A Ti/Au drain contact was then deposited on the back of the wafer. A 25nm ALD Al_2O_3 was used as the gate oxide, and a Ti/Ni/Au stack was deposited as the gate contact on top of the wafer.

From a simple CV analysis on the metal-isolation-semiconductor (MIS) structure, it's confirmed that the conductivity of the Ga_2O_3 epitaxial layer was successfully modulated by the Mg diffusion process for a depth of ~ 1.6 µm. The same MIS structure measured a reverse breakdown voltage of 466 V. However, when the surface is further doped with implanted Si^{++} layer, the formed NIN diode only blocks ~72V, the same as the final device blocking voltage. The VDBFET showed amazing transistor characteristics with decent saturation, on-current without any optimization, as well as a current on/off ratio > 10^9. Due to the compensation of electrons by Mg in the gate region, the transistor exhibited enhancement mode operation with a turn-on voltage of ~7V. The breakdown voltage, however, was only measured to be 72 V under a gate bias of 0 V.

4:30pm **MD+AC+EP-TuA-12 Electrical Properties of p-NiO/β-Ga_2O_3 Vertical PN Heterojunction Diode for Power Device Applications**, ***Youngkyun Jung***, *D. Chun,* Hyundai Motor Company, Republic of Korea

In this paper, the p-type NiO/β-Ga_2O_3 vertical pn heterojunction diode for power device application was fabricated, and the electrical characteristics of the device was evaluated. The β- Ga_2O_3 has a wide energy bandgap of about 4.8eV, and that is expected to be a material for next-generation power semiconductors with high breakdown voltage and low power loss. Compared to SiC (Silicon carbide) and GaN (Gallium Nitride), which are used as common materials for power semiconductors, it has a breakdown field (8MV/cm) that is about 3 times higher, and Baliga's FOM (3,400), which represents the semiconductor figure of merit, it has a value 4 to 10 times higher than that of GaN and SIC materials. Recently, β-Ga_2O_3 has been fabricated in the form of an epitaxial layer on a wafer and applied to power devices such as MOSFETs, MESFETs, Schottky barrier diodes, and pn junction diodes. The p-NiO has a wide band gap of 3.6 eV or more, p-type characteristics of NiO generally is induced by nickel vacancies or oxygen interstitials, that are defects provide the hole carriers. The carrier concentrations of p-NiO can be controlled in the range of 10^{16} to 10^{19} cm^{-3} with the amount of oxygen gas during the sputtering deposition process. The depletion region width of p-NiO/β-Ga_2O_3 can be changed according to the change in the carrier concentration of p-NiO. To fabricate the pn vertical heterojunction diode, p-NiO was deposited on the β-Ga_2O_3 epitaxial layer with a thickness of 250nm by using RF magnetron sputtering, and 100 nm of Ni metal for ohmic contact was deposited on the deposited p-NiO by using DC magnetron sputtering. The I-V characteristics of the fabricated pn heterojunction diode were measured by keithley 2410, and the C-V characteristics were measured by Keysight 4284A. As a result of measuring electrical characteristics, the pn heterojunction diode has a lower leakage current value than the previously reported Schottky Barrier Diode, and on/off ratio is about 10^9. When the carrier concentration of deposited p-NiO was $10^{19}cm^{-3}$, the turn-on voltage, current density, Ron value and breakdown voltage values of pn heterojunction diode were shown 2.2V, 242A/cm^2@4V, 17mΩ.cm^2@4V, and –465V respectively.

4:45pm **MD+AC+EP-TuA-13 Effects of Oxygen Reactive Ion Etching and Nitrogen Radical Irradiation on Electrical Properties of Ga_2O_3 Schottky Barrier Diodes**, ***Shota Sato***, *K. Eguchi,* Department of Physics and Electronics, Osaka Metropolitan University, Japan*; Z. Wang,* National Institute of Information and Communications Technology, Japan*; T. Kitada, M. Higashiwaki,* Department of Physics and Electronics, Osaka Metropolitan University, Japan

β-Ga_2O_3 has attracted great attention as a new wide bandgap semiconductor mainly for power devices. Oxygen reactive ion etching (O_2 RIE) is often used to remove a resist and/or an organic contamination in Ga_2O_3 device processing. However, this process usually causes damage to a Ga_2O_3 surface degrading device characteristics. On the other hand, we found that nitrogen (N) radical irradiation can significantly restore the Ga_2O_3 surface damage. In this study, we investigated effects of the O_2 RIE and N radical irradiation on electrical properties of Schottky barrier diodes (SBDs) fabricated on *β*-Ga_2O_3 (100) and (010) substrates.

Ga_2O_3 SBD structures were fabricated using unintentionally doped *β*-Ga_2O_3 (100) and (010) bulk substrates with an effective donor concentration of less than 2×10^{17} cm^{-3}. We evaluated electrical properties of the Ga_2O_3 SBDs fabricated on the substrates treated by four different processes: (a) no surface treatment, (b) O_2 RIE, (c) N radical irradiation, (d) O_2 RIE followed by N radical irradiation. The O_2 RIE was performed at an RF power of 50 W for 90 seconds. The N radical irradiation was conducted using an RF plasma cell in a molecular beam epitaxy growth chamber at a substrate temperature of 700°C and an RF power of 500 W for 2 hours.

We first studied current density–voltage (*J*–*V*) characteristics of the Ga_2O_3 (100) SBDs processed by the four different methods. In case of the devices with no treatment, a large variation of the turn-on *V* in a wide range of 0.5–1.1 V was observed. The O_2 RIE process further spread the variation to 0.2–1.0 V, indicating that the Ga_2O_3 (100) surface was more damaged. Furthermore, some devices showed kinks in their *J*–*V* curves. The curves with the kinks look like an overlap of *J*–*V* characteristics for a few area with different Schottky barrier heights under the anode electrode. In contrast, with and without the O_2 RIE, *J*–*V* characteristics of both SBDs treated by the N radical irradiation showed an almost constant turn-on *V* of 0.3 V and no kink. These results indicate that the N radical irradiation has effects to significantly restore the Ga_2O_3 surface damage and equalize the surface condition. Qualitatively the same effects of nitridation were confirmed for the Ga_2O_3 (010) SBDs.

In conclusion, we found that N radical irradiation is effective for restoring Ga_2O_3 surface damage, which leads to improvements in electrical properties of the Schottky interface.

This work was supported in part by the Development Program, “Next-Generation Energy-Saving Devices” of the Ministry of Internal Affairs and Communications, Japan (JPMI00316).

Advanced Characterization Techniques
Room Bansal Atrium - Session AC-TuP

Advanced Characterization Techniques Poster Session II

AC-TuP-1 Photoluminescence Spectroscopy of Cr^{3+} in β-Ga_2O_3 and $(Al_{0.1}Ga_{0.9})_2O_3$, ***Cassandra Remple,*** Materials Science & Engineering Program, Washington State University*; L. Barmore,* Dept. of Physics and Astronomy, Washington State University*; J. Jesenovec, J. McCloy,* Institute of Materials Research, Materials Science & Engineering Program, Washington State University*; M. McCluskey,* Dept. of Physics and Astronomy, Washington State University

Alloying β-Ga_2O_3 with Al_2O_3 to create $(Al_xGa_{1-x})_2O_3$ enables ultra-wide bandgap material suitable for applications deep into the ultraviolet. In this work, photoluminescence (PL) spectra of Cr^{3+} were investigated in monoclinic single crystal β-Ga_2O_3:Cr, 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 295 K to 16 K. For both materials at 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). The linewidths for AGO are larger for all temperatures due to alloy broadening. For both materials, the *R*-lines blue-shift with decreasing temperature. The (lowest energy) R_1 line is dominant at low temperatures due to the thermal population of the levels. For temperatures above ~50 K, however, the ratio of R_2 to R_1 peak areas is dominated by nonradiative combination. Additionally, Hall data was taken at low and elevated temperatures which demonstrated n-type behavior.

AC-TuP-2 Determining the Effects of Traps on the Effective Mobility of β-Ga_2O_3 MOSFETs using the Split C-V Method in Dark and Illumination Conditions and Pulsed I-V*, Ory Maimon,* George Mason University*; N. Moser,* Air Force Research Lab*; D. Chamria,* Colgate University*; K. Liddy, A. Green, K. Chabak,* Air Force Research Lab*; S. Pookpanratana, P. Shrestha,* National Institute of Standards and Technology (NIST)*; Q. Li,* George Mason University

Beta-gallium oxide (β-Ga_2O_3) high power and RF device performance is rapidly increasing due to the improved growth and fabrication methods developed in the last few years. Investigation of traps at and near the β-Ga_2O_3 and gate dielectric interface is critical for improving reliability and performance of β-Ga_2O_3 MOSFETs. Trap state energies can vary in the β-Ga_2O_3 bandgap, and their occupation can change with device bias. The trap states can also act as scattering sites, reducing the mobility. Here, we report on a study of effective mobility degradation due to traps at the Al_2O_3/β-Ga_2O_3 interface in lateral depletion-mode β-Ga_2O_3 MOSFETs using the split C-V method in dark and illumination conditions with wavelengths from 730 nm (1.7 eV) to 265 nm (4.7 eV) and pulsed I-V is used to further characterize the traps

The MOSFETs are fabricated on a (010) semi-insulating β-Ga_2O_3 substrate. A 50 nm Si-doped epi layer is grown as the channel with a target doping concentration of 2.4 x 10^{18} cm^{-3}. The ohmic contacts are formed using a Ti/Al/Ni/Au metal stack and annealed at 470 °C for 1 min in nitrogen. A 20 nm Al_2O_3 gate dielectric is deposited using plasma-assisted atomic layer deposition (PE-ALD). The transistors are fabricated with a constant L_G and L_{GS} of 2 µm and 0.5 µm, respectively, while L_{GD} varies between 0.5 µm, 5.5 µm, and 10.5 µm. Most FETs have a threshold voltage of -4 V, good linearity, and I_{ON}/I_{OFF} ratios between 10^7 – 10^9.

A D_{it} of 3 x 10^{11} eV^{-1} cm^{-2} up to 0.44 eV below the conduction band is determined using the conductance method. Using illumination gives deep trap concentrations 1.7 eV below the conduction band. We observe little change for wavelengths above 455nm (2.7 eV) but see increasingly larger flatband voltage shifts as wavelength decreases, indicating a larger D_{it} 2.7 eV below the conduction band. We observe an approximate 1.8x increase in the effective mobility under 265nm (4.7 eV), indicating that it is considerably lowered due to filled traps throughout the bandgap. We will present the analysis of the split C-V method in dark and illumination conditions, with a focus on the impact of traps on the mobility, and use pulsed I-V to analyze traps in comparison to the split C-V measurement.

AC-TuP-3 Advanced Characterization Methods for Scale-up and Improvement of β-Ga2O3 Substrates*, Robert Lavelle, D. Snyder, W. Everson, D. Erdely, L. Lyle, A. Balog, N. Alem,* Penn State University

Advanced characterization methods are required to scale-up and improve the quality and uniformity of β-Ga2O3 substrates. In addition to developing these methods, one of the key challenges is implementing characterization techniques at each stage of processing and combining these data to understand the interdependency of these steps and, ultimately, the impacts on device performance. PSU/ARL is uniquely positioned to help establish this vertically integrated feedback loop based on its β-Ga2O3 substrate processing experience and relationships with crystal and epi growers. PSU/ARL has characterized β-Ga2O3 crystals grown by multiple methods, including edge-defined film-fed growth (EFG) and Czochralski (Cz), and mapped full 2" substrates following chemi-mechanical polishing (CMP). In this poster, we will share these results focused on understanding the quality and uniformity of the substrates as well as advanced characterization methods, such as high-resolution x-ray diffraction (HRXRD) and transmission electron microscopy (TEM), for understanding the impacts of processing on defects and the fundamental material properties of the substrates. In this poster, we will highlight our recent progress on etch pit density (EPD) and defect mapping of full β-Ga2O3 substrates. This includes investigating the propagation of defects such as nanopipes and impacts on epi growth. As part of this work, we have utilized a variety of characterization methods from optical mapping of full 2" substrates to performing TEM of individual defects. We will also discuss how we implemented characterization methods, including HRXRD, white light interferometry (WLI), and atomic force microscopy (AFM), for improving the surface finish and minimizing subsurface damage during CMP of β-Ga2O3 substrates. These advanced characterization methods have been essential in producing high-quality, uniform substrates during the scale-up process. Finally, we will share our recent work on characterizing off-cut/off-axis substrates and different alloy compositions in collaboration with groups focused on researching crystal and epi growth methods.

AC-TuP-4 Vacancies in Electron Irradiated β-Ga_2O_3 Probed with Positrons*, Marc Weber, C. Halverson,* Washington State University*; B. Dutton, C. Remple,* Washington State University, United States Minor Outlying Islands (the)*; M. McCluskey,* Washington State University, US, United States Minor Outlying Islands (the)*; M. Scarpulla,* University of Utah*; J. McCloy,* Washington State University, United States Minor Outlying Islands (the)

Positron annihilation spectroscopy is a powerful tool to evaluate vacancies and vacancy-related defects. To extract absolute defect concentrations data on reference samples or from other techniques must be available. We have examined bulk grown and epi-layer β-Ga_2O_3 material before and after high dose electron irradiation. Pre-existing and generated defects are probed by depth resolved positron Doppler Broadening and FTIR. Compared to other semiconducting materials, the anisotropic electron momentum distribution of β-Ga_2O_3 poses challenges. Data from samples oriented in the [100], [010], and [001] direction are examined and compared to earlier experiments on oxygen annealed β-Ga_2O_3[1] and recent theoretical work.[2] Subsequent annealing studies will further assist in the identification of the created defects. This work generously supported by the Air Force Office of Scientific Research under award number FA9550-18-1-0507 monitored by Dr. Ali Sayir.

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AC-TuP-5 Artificial Intelligence Assisted Vacancy Detection via 3D Microscopy in Doped and Undoped Ga_2O_3*, Prachi Garg, J. Sarker,* Department of Materials Design and Innovation, University at Buffalo*; A. Uddin Bhuiyan, L. Meng,* Department of Electrical and Computer Engineering, The Ohio State University*; H. Zhao,* Department of Electrical and Computer Engineering & Department of Materials Science and Engineering, The Ohio State University*; K. Reyes, B. Mazumder,* Department of Materials Design and Innovation, University at Buffalo

Recently, gallium oxide (Ga_2O_3) has attracted attention in high-power electronics and Schottky barrier diodes, due to their wide bandgap of ~4.8eV and critical breakdown strength of ~8 MV/cm. However, the low electron mobility of Ga_2O_3 makes it crucial to dope with group IV elements (Si, Sn or Ge) in order to achieve desired electrical conductivity. This dopant incorporation in Ga_2O_3 contributes to the formation of Ga vacancies. While

the inherent O vacancies in Ga_2O_3 does not contribute to the electrical conductivity, the formation of Ga vacancies upon doping tends to trap the dopant atoms resulting in charge compensation effect in the material. To further improve semiconductor properties, defects like vacancies are introduced in a controlled manner, which have significant effect on its optical/charge transfer properties. Therefore, identifying and detecting these cationic vacancies are impactful for transport properties, however it is very challenging to detect vacancies from an atomic perspective using nano-analytical tools. Atom probe tomography (APT) is the only characterization tool that is capable of providing atomic resolution in 3D space. However, the latent features remain hidden in the tool complexities and large dimensional data, making it difficult to detect vacancies and distinguish them from missing atoms using APT alone. In this work, we developed a unique approach by integrating artificial intelligence with microscopic data to map the vacancy position in real atom probe data. Here, we applied a deep learning model named U-net for vacancy extraction on the 3D microscopic APT data. U-net is the image segmentation model which works in an end-to-end setting. A raw image is fed to the model, that goes within carefully tuned architecture and results in a segmented image i.e. feature map in this case. This model is trained on the synthetically generated Ga_2O_3 structure using MD simulation software named LAMMPS (Large scale Atomic/Molecular Massively Parallel Simulator. Large structure is generated and sliced into voxels, fed into U-net model to train it on vacancy identification in each slice. Once the U-net model is trained, we use the APT data, slice it and feed into the model to detect the vacancies in real dataset. The trained U-net model will automatically analyze the APT data to learn and predict the local structure including vacancies to understand the vacancy distribution in doped and undoped Ga_2O_3 structure. This work will provide an advancement in understanding the effect of Ga vacancies in Ga_2O_3. This work can also be expanded to study similar materials systems for developing future high-power transistors and optical devices.

AC-TuP-6 Silicon Ion Implantation in β-Ga_2O_3: Effect of Temperature on Atomic Damage and Recovery, ***Naomi Pieczulewski,*** *K. Gann,* Cornell University*; T. Asel, B. Noesges,* Air Force Research Laboratory*; K. Heinselman,* National Renewable Energy Laboratory*; M. Thompson, D. Muller,* Cornell University

Si implantation is a promising strategy to reduce contact resistance and improve Ga_2O_3 device performance.[1] Recent reports have shown a variety of phase transformations into Ga_2O_3 polymorphs from the β phase upon ion implantation.[2,3] Previously our group has found that by using high angle annular dark field (HAADF) and annular bright field (ABF) scanning transmission electron microscopy (STEM) imaging, we can accurately identify γ-phase of Ga_2O_3.[4] Here, we present a systematic study of high Si implant doses over a range of implant temperatures from liquid nitrogen temperature to 600°C to investigate the limits of damage recovery. We found that the kinetically favored defect structure is γ- Ga_2O_3 under the investigated implant conditions and the implanted films retain β-Ga_2O_3 resulting in fast and clean recovery.

MBE grown UID β-Ga_2O_3 [010] film was implanted with Si over a 100nm profile targeting a total carrier concentration of $5x10^{19}$ to $1x10^{20}cm^{-3}$. The implanted films were characterized by STEM to probe defects at the atomic scale, supplemented by X-ray diffraction (XRD) and Rutherford Back Scattering (RBS). We observe implantations performed at both room temperature and low temperature cause a phase transformation into γ-Ga_2O_3 as well as interstitial Ga defects in β-Ga_2O_3, but also retain significant β-Ga_2O_3. Crystallinity in the low temperature implant indicate significant dynamic annealing either during implantation or during warming back to room temperature. Implantation performed at a high temperature shows significantly less lattice damage and retains complete β-Ga_2O_3. Thermal activation by post-annealing heat treatment is required on all samples to electrically activate carriers.

Finally, lattice recovery and Si activation was investigated after annealing the Si implanted films at 950°C for 20 minutes under high purity nitrogen. Carrier activation was observed in the control implant starting only after a couple minutes, indicating the retained β-Ga_2O_3 enables fast recrystallization into recovered film.All films showed good recovery and significant dopant activation, indicating the limits of damage recovery can be still pushed.

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AC-TuP-8 Kinetics of Compensation in Sn-doped Ga_2O_3 During O_2 Annealing Revealed by FTIR and Modelling, *J. High, H. Yang, N. Rock,* ***Mike Scarpulla,*** University of Utah

It is well known that annealing n-type doped β-Ga2O3 in air or O_2 produces insulating surface layers on the micron scale; however the microscopic mechanisms remain a mystery. Besides the identity of the defects involved, the locations of generation and transport are unknown.

At this time, V_{Ga}, V_O and their complexes are believed to be the dominant stable native defects but the mechanisms of their formation are unknown. Do V_{Ga} form at structural defects and interfaces then diffuse to permeate the material, or do Frenkel pairs nucleate homogeneously and the Ga_i diffuse away to sinks? How is the information about oxygen richness imposed transmitted from the surfaces inwards to the bulk; do O_i play any transient role in mediating these processes? Such details still have not been addressed, and can not be distinguished by their effects on net charge alone; some orthogonal data such as formation or migration barriers must also constrain hypotheses in order to determine the most likely.

We have been utilizing FTIR transmission through wafers approximately 500 µm thick to reveal the kinetics of the conducting-to-insulating transition during annealing. In thick samples, a mechanism with diffusion constant many orders of magnitude faster than that found near the surface (up to ~ 1 µm) using electrical methods would be required. Put more concretely, if only the previously-determined mechanism is present, the insulating transition would take centuries in wafers while only days to weeks are required near 1000 °C in pure O_2.

We developed a coupled defect diffusion, carrier density, dielectric function, multilayer optics model of the samples with which we can test hypotheses for the kinetics of compensating defect formation and transport. Our model spans from the bandgap near 5 eV to the limiting 2-phonon absorption at 1500 cm^{-1} and, after inclusion of POP phonon-limited momentum scattering lifetime in the Drude component, reproduces the data extremely well. With this level of modelling, we show with high confidence that at least two diffusion-mediated processes are required to reproduce the data. We review possible mechanisms and provide evidence on the kinetic barriers for what is presumably a native defect driven process. Fortunately, the fidelity and predictiveness of computations of defect energetics and migration barriers now allow differentiation between possible mechanisms; we hope that these experiments will motivate detailed studies to uncover the detailed mechanisms of defect processes in Ga_2O_3 and beyond.

AC-TuP-9 Cation Vacancy and Dopant Diffusion in β-Ga2O3, ***Nathan David Rock,*** *A. Levin,* University of Utah*; A. Bhattacharyya,* University of California Santa Barbara*; H. Yang, B. Eisner,* University of Utah*; S. Krishnamoorthy,* University of California Santa Barbara*; M. Scarpulla,* University of Utah

Mechanistic understanding of native and impurity defect diffusion and reaction processes in Ga2O3 is necessary for advanced fabrication of devices and for the long-term reliable operation of those devices.The diffusion of native and impurity atoms and their incorporation into various point defects and complexes is mediated by native defects.Thus, understanding the diffusion of native defects is fundamental to understanding all diffusion processes.Unlike impurities, vacancies are difficult to study because of the difficulty of measuring their concentration.Additionally, the mechanisms of formation of native defects are unknown; for example, cation vacancies may be introduced at surfaces and diffuse inwards, or interstitial-vacancy pairs may form in the bulk with interstitials diffusing outwards.

We introduced superlattices (SLs) of alternating $(Al,Ga)_2O_3/Ga_2O_3$ grown by OMVPE in order to make visible the flux of cation vacancies using Al as a tracer.We demonstrate that in the case of SLs grown on Sn-doped substrates, the diffusion of Al is mediated by the transient diffusion of a large concentration of mediating defects (presumed to be VGa or complexes thereof) from the substrate into the epilayers.This results in faster diffusion near the Sn-doped substrate and slower near the free surface indicating that the introduction of VGa from the free surface is insignificant at the at% level compared to the supply in the substrate.In the case of SLs grown on Fe-doped substates, the diffusion of Al is much slower and spatially-uniform indicating a uniform density of meditating defects vs depth.Additionally, we document the co-diffusion of Sn and Fe out of the substrates and through the SLs – this implies that VGa is not diffusing alone

but rather as complexes or with high-correlation with Fe or Sn.This implies that the rates measured are not those of the VGa itself but rather a slowed rate from the mutual effects of solute drag.The role of oxygen is also investigated – annealing in O2 is generally needed for dopants to diffuse, however the role of O in the diffusion of pre-existing VGa in the substrate is not clear.In addition to the model of vacancy-mediated diffusion introduced last year, we also report on coupled drift-diffusion-reaction-Poisson models for simultaneous diffusion of V_{Ga}, Sn, and Fe.We also have documented the presence and diffusion of various other impurities which has implications for device stability.We estimate the contributions of chemical and electrical potential gradients (e.g. surface fields and dopant concentration steps) in the mass transport.

Bulk Growth
Room Bansal Atrium - Session BG-TuP
Bulk Growth Poster Session II

BG-TuP-5 β-Ga_2O_3 Single Crystal Growth by EFG Method using Die with Multi-Slit Structure, ***Yeon-Geun Seong**, Y. Moon,* Axel, Republic of Korea*; H. Jang, S. Choi, C. Min-Ji, S. Seo, M. Park, Y. Jang, W. Lee,* Dongeui University, Republic of Korea*; J. Kang,* Axel, Republic of Korea

β-$Ga_2O_3$is attracting attention as a next-generation power semiconductor. β-Ga_2O_3 has a high bandgap of 4.9eV and a high breakdown voltage of 8MV/cm. In addition, β-Ga_2O_3 grown by the EFG (Edge Defined Film-Fed Growth) method is superior to other power semiconductor materials such as SiC and GaN due to its fast growth rate and low manufacturing cost. However, since the β-Ga2O3 crystal grown by the EFG method grows in a ribbon morphology, the number of wafers that can be extracted from one ingot is small. [1-4]

In this study, the thickness of the ingot was increased through a die with multi-slit structure. Crystal growth from multi-slit structure is divided into 'diameter direction', which determines the size of the wafer, and 'thickness direction', which determines the extraction numbers of wafer. As a result of β-Ga2O3 growth experiments using Muliti-Slit Die, we found that thick crystal growth is difficult if the growth rate in the diameter direction is too fast, and polycrystals are easily to occur if the growth rate in the thickness direction is too fast. Therefore, in order to overcome these problems, the two-dimensional temperature distribution and the temperature gradient in the vertical direction were adjusted to secure reproducibility to stably grow thick crystal with high crystallinity.

As a result of the experiment, various process conditions, such as the type and structure of insulation, three-dimensional temperature gradient, and pulling speed, had a more sensitive effect on the growth of thickness direction in multi-slit die compared with single-slit die. By adjusting the thermal balance of upper and lower parts of crucible and the temperature gradient of die in diameter direction and thickness direction, the growth of thick β-Ga2O3 single crystals was successfully achieved. This result can contribute to lower the manufacturing cost of Ga2O3 crystals as a substrate for power semiconductor fabrication.

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Electronic and Photonic Devices, Circuits and Applications
Room Bansal Atrium - Session EP-TuP
Electronic and Photonic Devices, Circuits and Applications Poster Session II

EP-TuP-6 Investigating the Properties of β-Ga_2O_3 Schottky Diodes on MOCVD-Grown (001) Drift Layer, ***Prakash P. Sundaram**,* University of Minnesota, USA*; F. Alema, A. Osinsky,* Agnitron Technology*; S. Koester,* University of Minnesota, USA

In this study, we investigate the electrical properties of Schottky barrier diodes (SBD) fabricated on epitaxial layers grown on (001) β-Ga_2O_3 (GOX) by metal-organic chemical vapor deposition (MOCVD). While various growth methods have been used for epitaxy of GOX, MOCVD has emerged as the most established technique for large-scale commercial growth. As far as the orientation of GOX is concerned, the principal planes, namely (100), (010), and (001) are often used for homoepitaxial thin-film growth. However, of these, only the (100) and (001) surface orientations are cleavage planes, making large diameter (> 6”) wafer production possible. Despite the advantage offered by the (001) orientation, growth of high-quality MOCVD films on (001) GOX has not been reported. Here, we report the properties of GOX Schottky diodes on MOCVD-grown (001) films and compare the results to those grown on (010) substrates.

For this study, SBDs were fabricated on a Si-doped (001) 3.3-µm-thick homoepitaxial GOX thin film grown by MOCVD, where Ni was used as the Schottky metal. We also fabricated SBDs on a co-grown (010) film for comparison. The doping density in the films were in the range of 3-7 × 10^{15} cm^{-3} and 1.5-1.8 × 10^{16} cm^{-3} for the (001) and (010) samples, respectively, as determined by C-V measurements. From the room-temperature forward current density vs. voltage (J-V) characteristics, the ideality factor, Schottky barrier height (SBH), and on-resistance for (001) SBDs were extracted to be 1.07 eV, 1.08, and 25 mΩ-cm^2, respectively. The SBH for (001) was found to be ~ 0.17 eV lower than on (010). Further temperature-dependent analysis of the forward J-V characteristics show an apparent Schottky barrier inhomogeneity for the (001) samples. Reverse breakdown measurements showed an average breakdown voltage of 235 V, which is slightly lower than the value of 325 V predicted from TCAD. Poole-Frenkel analysis of the reverse J-V-T characteristics revealed excess leakage mechanism associated with the presence of traps at 0.31 eV below the conduction band which could also explain the early breakdown in the (001) layers. In summary, our study provides insights into the electrical characterization of SBDs fabricated on (001) GOX epitaxial films grown by MOCVD and highlights the need for optimizing growth parameters to improve film quality and device performance.

EP-TuP-8 Operation of β-Ga2O3 Field-effect Transistors at 650 °C, ***James Spencer Lundh**, H. Masten,* National Research Council Postdoctoral Fellow residing at US Naval Research Laboratory (DC)*; F. Alema, A. Osinsky,* Agnitron Technology, Inc.*; A. Jacobs, K. Hobart, T. Anderson, M. Tadjer,* US Naval Research Laboratory

The ultrawide bandgap of β-Ga2O3 (4.8 eV) allows high voltage/temperature operation, making it enticing for extreme environment electronics. Potential applications include space exploration, aeronautics, and defense, which can have operating environments with temperatures greater than 600°C. As such, performance and reliability at these high operating temperatures must be characterized and understood in order to optimize devices for expected, reliable, and stable operation. In this work, we report operation and electrical characterization of β-Ga2O3 metal-oxide-semiconductor field-effect transistors (MOSFETs) at temperatures up to 650°C to lay the groundwork for potential deployment in extreme environments.

Using Agnitron’s Agilis 100 MOCVD reactor, a 300 nm thick UID Ga2O3 buffer, 30 nm thick 10^{18} cm^{-3} Ga2O3:Si channel, and 10 nm thick 10^{19} cm^{-3} Ga2O3:Si contact layers were grown on (010) β-Ga2O3:Fe substrates. Ti/Au Ohmic contacts were deposited (e-beam), lifted off, and annealed (470°C, 1 min, N2). Next, a 20 nm thick Al2O3 gate dielectric was deposited using ALD. Finally, Pt/Au gate contacts were deposited (e-beam). The devices had a channel width/length of 75/15.5 µm, gate length of 3 µm, and a drain-gate spacing of 10 µm. A cross-sectional schematic of the device structure is shown in Fig. 1. The MOSFETs had a Hall mobility of 170 $cm^2V^{-1}s^{-1}$, sheet carrier concentration of 1.74x10^{12} cm^{-2}, sheet resistance of 21.02 kΩ/sq, and specific contact resistivity of 5.26x10-4 Ωcm^2 at room temperature. For high temperature measurements, a DC/RF MicroXact probe station was used along with a Keithley 4200. All measurements were performed under vacuum at base temperatures (T_{base}) from 30°C to 654°C. The devices were held at T_{base}=654°C for 1 hr. DC output and transfer characteristics of a Ga2O3 MOSFET are shown in Fig. 2. From Fig. 2(a), at 654°C, there is >3× increase in the maximum Ids (Vgs = 5 V) as compared to at 30°C. In Fig. 2(b), a negative threshold voltage shift is observed as T_{base} is increased. Furthermore, the increase in T_{base} also led to a significant increase in the OFF-state leakage; from 30°C to 654°C, the leakage current increased by five orders of magnitude. In Fig. 3, both Ids and Ig are plotted as a function of Vgs for four MOSFETs at 654 °C. As shown, Ig is three orders of magnitude smaller than Ids in the OFF-state, indicating that the gate is not the primary leakage path at high temperatures. After returning to room

temperature, the OFF-state leakage reduced to pre-heated levels and there was a slight improvement in the ON/OFF ratio.

Heterogeneous Material Integration
Room Bansal Atrium - Session HM-TuP
Heterogeneous Material Integration Poster Session II

HM-TuP-1 Bond-and-Thin Process for Making Heterogeneous Substrate with a Thin Ga_2O_3 Layer om Polycrystalline SiC Substrate, ***Alex Usenko***, *A. Caruso,* University of Missouri-Kansas City*; S. Bellinger,* Semiconductor Power Technologies

Making Power Semiconductor Devices on starting heterogeneous engineered substrates gives numerical advantages over making them on bulk blanket wafers.

For β-Ga_2O_3 it allows to mitigate its critical disadvantage – low thermal conductivity that heavily limits its applications to power semiconductor devices.

In our process flow, we bond 100 mm cmmercially available polycrystalline SiC wafer to 100 mm commercially available β-Ga_2O_3 wafer using room temperarature surface activation bonding process. Then we thin the initial β-Ga_2O_3 to a mnimum thickness needed for desired device voltage.

As each micron of β-Ga_2O_3 withstand up to 800V, the typical final thickness is several microns.

Using polycrystalline SiC substate is for 2 reasons - it is more than 10X cheaper than single crystalline one, and it can have 100X lower electricall resistance compared to aregular nitrogen doped SiC. Indeed, the substrate here is just mechanical support and electrical contact, no semiconductor properties needed. For processes based on epitaxial growth - crystalline lattice is needed, while our process - wafer bonding - is independent on crystal structure.

Next we etch the continuous β-Ga_2O_3 layer into islands equal in shape and area to future power chips to be made on them. Reason is, the continuous layer will not withstand ~1000C processing steps for making MOSFETS and even Schottky diodes. The continuous layer breaks due to difference in thermal expansion. While the islands withstand the thermal processing. The process is being patented.

HM-TuP-3 Design of 10 kV P-Diamond/I-Ga_2O_3/N-Ga_2O_3 Power PN Diodes, ***Hunter Ellis***, *K. Fu,* Department of Electrical and Computer Engineering, University of Utah

β-Ga_2O_3 is a promising ultra-wide bandgap semiconductor material with a unique combination of ultra-wide bandgap, high breakdown field, and large wafer size [1]. Devices based on β-Ga_2O_3 are expected to be smaller, cheaper, more efficient, and more temperature- and power-resistant than other semiconductors [1,2]. However, several obstacles stop β-Ga_2O_3 from being a mainstream electronics material. Specifically, the lack of effective P-type dopants and low thermal conductivity pose significant challenges [1,3]. Since a PN junction is the basic building block for device design, the absence of P-type β-Ga_2O_3 has prevented the full exploitation of its properties, and conventional device design strategies used for Si cannot be transferred to β-Ga_2O_3. On the other hand, high thermal conductivity is critical in electronic devices to minimize heat damage and reduce the likelihood of failure [1, 3].

A P-type diamond and N-type Ga_2O_3 PN heterostructure could address these issues. Diamond could form an ideal heterojunction with β-Ga_2O_3 due to their ultra-wide bandgaps. Diamond is relatively easy to make P-type and has high thermal conductivity; a simulated PN junction is shown in the supplemental document [3,4]. This structure can simultaneously address both problems. However, significant work in device design and integration of epitaxial growth is needed to realize this concept.

In this study, we established a model for the PN heterojunction. We investigated the energy band diagram for the P-diamond/I-Ga_2O_3/N-Ga_2O_3 structure, edge termination to mitigate electric field crowding, drift layer design (I-Ga_2O_3) to increase the breakdown voltage and reduce the on-resistance, and temperature dependence. We successfully designed 10 kV P-diamond/I-Ga_2O_3/N-Ga_2O_3 power PN diodes, and the results are very promising for this type of ultra-wide bandgap PN heterojunction. Effects of interface states on device performance were also investigated due to the importance of epitaxial growth.

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HM-TuP-5 Heterogeneous Material Integration, ***Yash Mirchandani***, Syrnatec

The use of UWBGs (Ultra-Wide Bandgap Semiconductors) based power converters is an emerging technology that will revolutionize power electronics industries.Space-rated DC-DC converters' performance and power density are primarily limited by high-power Metal Oxide Semiconductor Field Effect Transistors (MOSFETs). Power MOSFETs are very susceptible to damage and degradation from the irradiation found in space, especially ionizing radiation. As a response to the current technology gap, Syrnatec in collaboration with University at Buffalo has developed a revolutionary Ga2O3 technology-based UWBGs. These Ga2O3 MOSFETs are capable of demonstrating more robustness to single event effects than their rad-hard power MOSFET counterparts. Because Ga2O3 MOSFETs do not have a metal oxide layer, they are very robust to ionizing radiation, which prevents charge entrapment from TID in high radiation environments. After exposure to 500 krad (Si) ionizing doses, early radiation tests on first generation Ga2O3 MOSFETs showed less than 4% threshold voltage variation (VTH) and less than 3% RDSON change. When the devices were in the OFF state, higher variation was reported (18% VTH and 8% RDSON). In second generation Ga2O3 MOSFETs, no performance degradation has been observed from TID to 1.0 Mrad (Si).Syrnatec's Gallium Oxide MOSFET, an upcoming wide bandgap material that is not only inherently radiation tolerant, but is also suitable for operating in environments with extreme temperatures such as lunar night, where the temperature changes from -153 degrees Celsius to 123 degrees Celsius , and -125 degrees Celsius to 80 degrees Celsius.

Syrnatec will incorporated its Ga2O3 technology into DC-DC converters with a bulk voltage of 20% to 80% and a trickle voltage of above 80%. With a maximum and minimum bulk charge timer (validated as the charge parameters), a Trickle voltage per cell (to be 2V), Boost and trickle voltage settings (Boost is 120% of the rated voltage, Trickle is 2V) and a Device switch off setting (tested on a battery under 20%). With no errors in over voltage and over current test conditions at 150% rated input for 1 sec out of every 10 seconds while maintaining an average of 100% overall rated values for the other 9 seconds. In addition, we have evaluated the success of fault detection across the entire Military Grade Temperature flow. In both buck and boost modes, power conversion efficiency exceeded 96% over the entire temperature range.

Overall, Ga2O3 based power converters can bring several novel features to the US commercial market, including high breakdown voltage, high thermal conductivity, wide bandgap, and low cost.

HM-TuP-6 Si/Ga_2O_3 and GaAsP/Ga_2O_3 P-N Diodes via Semiconductor Grafting, *J. Zhou, D. Kim, H. Jang, Q. Lin,* ***Jiarui Gong***, University of Wisconsin - Madison*; F. Alema, A. Osinsky,* Agnitron Technology Inc.*; K. Chabak, G. Jessen,* Air Force Research Laboratory*; S. Pasayat,* University of Wisconsin - Madison*; C. Cheung, V. Gambin,* Northrop Grumann*; C. Gupta, Z. Ma,* University of Wisconsin - Madison

Ga_2O_3, an ultrawide-bandgap semiconductor, has attracted substantial attention in recent years due to its exceptional electronic properties and its vast potential in power electronics and solar-blind optoelectronics [1]. Despite these attractive properties of Ga_2O_3, there are some challenges to be addressed. For instance, the long-standing issue of lack of p-type doping in Ga_2O_3 has persisted [2]. The inefficiency stems from high ionization energy of acceptors when using the common dopants in Ga_2O_3. As a result, the design and fabrication of high-performance bipolar Ga_2O_3 devices, such as p-n diodes, and HBTs, are still in the research and development stage.

Semiconductor grafting [3], which enables the formation of heterostructures between two arbitrary monocrystalline semiconductors, could be the approach to overcoming the current constraints through the creation of Ga_2O_3 heterostructures, wherein a foreign semiconductor with good p-type doping to integrate with Ga_2O_3 at the atomic level. In this approach, an ultrathin oxide (UO) layer at sub-nanometer scale serves both

as the interfacial passivation layer and an effective quantum tunneling layer. In the present case, the surface Ga_2O_3 layer and the possible native oxide of Si should have played the role of the UO layer in the grafting approach.

Employing the semiconductor grafting technology, two types of Ga_2O_3 heterojunctions are created, including Si/Ga_2O_3 and GaAsP/Ga_2O_3, to address the current challenges of ineffective p-type doping in Ga_2O_3 and lack of bipolar devices. In these two structures, p-type Si and p-type GaAsP nanomembranes (NM) are released from their respective epi substrates, transfer-printed and then subsequently chemically bonded to the n-type Ga_2O_3 substrates, forming PN abrupt heterojunctions, and the grafted heterostructures were subsequently fabricated into PN diodes. Their respective diode schematics are shown in Figs. 1 (a) and (b), with preliminary I-V curves for both diodes displayed in Figs. 1 (c) and (d). Both Si/Ga_2O_3 and GaAsP/Ga_2O_3 exhibit excellent rectifying behaviors with rectification ratios of 10^7 and 10^3 at ±2V, respectively. Meanwhile, their ideality factors are characterized to be 1.13 for Si/Ga_2O_3 diode and 1.35 for GaAsP/Ga_2O_3 diode.

In conclusion, we have demonstrated the feasibility to fabricate Ga_2O_3 bipolar devices via the semiconductor grafting approach. The demonstration of the high-performance Si/Ga_2O_3 and GaAsP/Ga_2O_3 PN diodes could lead to functional Ga_2O_3 HBTs in the near future.

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Material and Device Processing and Fabrication Techniques Room Bansal Atrium - Session MD-TuP

Material and Device Processing and Fabrication Techniques Poster Session II

MD-TuP-1 Growth of Room Temperature Polycrystalline β-Gallium Oxide Thin Film, ***Damanpreet Kaur***, *M. Kumar,* Indian Institute of Technology Ropar, India

Gallium oxide as an ultra-wide band gap semiconductor can exist in five different polymorphs – α, β, γ, κ, and ε – with different crystal structures and slightly different band gaps in the range of 4.6-5.3 eV.[1] The β-Ga_2O_3 is the most stable and most widely studied phase with intrinsic solar-blindness, band gap of 4.8 eV, high chemical and thermal stability, high breakdown voltage and high radiation hardness. Most of the existing literature have reported the fabrication of crystalline β-Ga_2O_3 at elevated temperatures (> 300°C) with no report on room temperature crystallization of gallium oxide.[2, 3] The material is either grown at a high temperature or it is annealed for achieving crystallization. The room temperature growth of gallium oxide is often reported to be amorphous in nature.

Herein, we report the formation of good quality polycrystalline β-Ga_2O_3 on *c*-plane sapphire at room temperature via RF Magnetron Sputtering. Grazing incidence X-ray Diffraction scans in the ϑ-2ϑ mode shows the peaks corresponding to the formation of polycrystalline peaks of β-Ga_2O_3. There is a shift in the peaks implying a strain in the films. Atomic Force Probe microscopy images reveal the formation of large grains which might be the cause of the strain in the films grown at room temperature. As a simple proof of concept, a photodetector with interdigitated Au electrodes was fabricated which showed a low dark current (~ 8 nA at +5 V) and a two order of magnitude (~ 0.46 μA at +5 V) enhancement upon 254 nm illumination.

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MD-TuP-2 Performance and Traps of Ga_2O_3 Schottky Barrier Diodes with Mesa Structure, ***Min-Yeong Kim***, NIST-Gaithersburg, Republic of Korea; *O. Maimon,* NIST-Gaithersburg; *N. Hendricks, N. Moser,* Air Force Research Laboratory, USA; *S. Pookpanratana,* NIST-Gaithersburg; *S. Koo,* KwangWoon University, Korea; *Q. Li,* George Mason University

Among the ultrawide bandgap materials, Ga_2O_3 is expected to surpass the trade-off relationship between breakdown (BV) and on resistance ($R_{on,sp}$). However, the Ga_2O_3 vertical Schottky barrier diode (SBD) still cannot achieve the theoretical breakdown electric field. To improve electric field management, device designs incorporating field rings, junction termination extension, field plates, and mesa structure could be used to reduce the leakage current in the reverse bias state. The edge termination technique has been demonstrated to extend the breakdown voltage close to the ideal value that is determined by the material properties.[1] Fabricating mesa structures for edge termination can introduce defects and charge traps. Deep level traps can negatively affect the performance of devices by trapping charge carriers, resulting in reduced minority carrier lifetime and increased leakage current.

Here, we analyzed the characteristics of Ga_2O_3 SBDs with and without the mesa structure. The SBDs were fabricated on Si-doped β-Ga_2O_3 grown by halide vapor phase epitaxy (HVPE) on a Sn-doped ($6x10^{18}$ cm^{-3}) (001) β-Ga_2O_3 substrate. In the SBD with mesa structure, the circular mesa with a diameter of 162 μm and a depth of 500 nm was formed around anode electrodes. The Ti/Au metal stack on the polished back side of the substrate acted as a cathode while Ni/Au/Pt layers on the epitaxy acted as the anode electrode. After the fabrication process, current-voltage (I-V) measurements were performed as shown in Figure 1a. From the results, the $R_{on,sp}$ at 1 V are 6.9 Ω•cm^2 and 7.9 Ω•cm^2 in planar and mesa SBDs, respectively. In addition, the leakage current at -165 V is reduced by approximately 99.9% in the mesa structure. Figure 1 (b) shows the reverse bias characteristics of the SBDs, where the SBDs with mesa structure have approximately 2.75 times higher BV than SBDs without a mesa structure. Deep level defects were investigated by deep level transient spectroscopy (DLTS), and the SBDs with different structure have similar trap energy levels shown in Figure 2. In general, the trap density is larger in the SBD with mesa structures, however, the trap near the 3.0 eV is only detected for the SBD without the mesa structure and this defect is related to surface contamination. [2] Furthermore, we will extend the study by performing the cathodoluminescence (CL) spectroscopy to get radiative defect information of the SBDs which could be related to the DLTS results. We will discuss these results in light of the enhanced electrical performance of SBDs with mesa structures.

MD-TuP-4 Evolution of Lattice Distortions Throughout Various Stages of (010) β-Ga_2O_3 Substrate Preparation, ***Michael Liao***, National Research Council Postdoctoral at the U.S. Naval Research Laboratory; *N. Mahadik,* Naval Research Laboratory; *R. Lavelle, D. Snyder, W. Everson, D. Erdely, L. Lyle, N. Alem, A. Balog,* Penn State University; *T. Anderson,* Naval Research Laboratory

Meticulous preparation of substrates – in particular chemical mechanical polishing – is vital to many subsequent processes such as epitaxial growth, device fabrication and wafer bonding. After slicing substrates from boules, the rough substrates require lapping and polishing to achieve surfaces for epitaxial growth. However, lapping and aggressive polishing introduce sub-surface damage even if smooth surfaces are achieved.[1] Sub-surface damage manifests itself as lattice distortions such as tilt and strain, as well as generation of extended defects. The lattice distortions can be assessed using X-ray diffraction along different scanning axes. Previous work has been done to optimize polishing parameters to simultaneously achieve smooth (< 0.5 nm rms roughness) and subsurface-damage-free substrates.[2] Interestingly, it was found that the damage induced by wafer slicing was not only predominately lattice tilt, but the tilt was preferentially oriented along the [100] crystallographic axis. In this current work, we investigate the evolution of sub-surface damage of Czochralski-grown (010) β-Ga_2O_3 wafers that have undergone various preparation stages: wire sawn surfaces, lapping, and final polished surfaces. Multiple asymmetric reciprocal space maps (RSM) in the glancing incidence geometry were measured along different zone axes to deconvolve the contributions of lattice tilt and strain from sub-surface damage. For the wire sawn rough surface, the (420) RSM shows ~2.4× higher broadening along the ω-scanning axis, which is an indication that the nature of lattice distortion is predominately lattice tilt. Furthermore, this broadening was asymmetrical, which is an indication that the lattice tilt is anisotropic and could be related to the anisotropic elastic properties for various β-Ga_2O_3crystal planes. This was in contrast to the polished sample, where the distortion due to tilt was mostly removed, and

there exists significantly reduced residual strain, indicated by small broadening in the ω:2θ scanning axis. These results are analyzed using the theoretical calculations of β-Ga_2O_3 elastic properties[3] to obtain insight on its unusual response to mechanical deformation during the wafer slicing and lapping process.

This research was performed while M.E.L. held an NRC Research Associateship award at the U.S. Naval Research Laboratory.

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MD-TuP-5 Investigation of In-Plane Anisotropy of In-situ Ga etching on (010) β-Ga_2O_3, *Abishek Katta,* Arizona State University*; F. Alema, W. Brand, A. Osinsky,* Agnitron Technologies*; N. Kalarickal,* School of Electrical, Computer and Energy Engineering, Arizona State University

We report on 'in-situ' MOCVD Ga etching using the metal organic Ga precursor triethylgallium (TEGa) and the in-plane anisotropy of the etch characteristics. Etch rates exceeding 8µm/hr is demonstrated at high TEGa flow rates and a substrate temperature >900°C. Significant in-plane anisotropy in etching is observed on (010) β-Ga_2O_3 samples with trenches formed along [001] direction showing the smoothest sidewalls.

Many promising device structures used in Ga_2O_3, like trench SBDs, trench MOSFETs, FinFETs etc require fabrication of 3-D structures like fins and trenches. Several etch techniques have been reported, including ICP-RIE, wet etching and metal assisted chemical etching. However, most of these techniques result in angled sidewalls and surface damage. Previously, exposure to metallic Ga was shown as a promising technique for etching Ga_2O_3, using the suboxide reaction 4Ga (s)+ Ga_2O_3 (s)—>3Ga_2O(g). In this work, we show that the suboxide reaction can also proceed by using TEGa as the Ga source with the Ga_2O_3 samples held at high temperature inside an MOCVD reactor.

The etching experiments were carried out in an Agnitron Agilis 100 MOCVD oxide reactor with a far injection showerhead. The variation in etch rate as a function of substrate temperature and TEGa flow rate was studied. Etch rate increases with substrate temperature till 900°C, above which no significant increase is observed. The etch rate also increases linearly with TEGa flow rate, eventually saturating at high flow rates. At T_{sub}=900°C and 1000°C, etch rates exceeding 8µm/hr is obtained, making it possible to fabricate deep trenches and high ASR 3-D structures. We also investigated in-plane anisotropy by using spoke wheel structures patterned on (010) β-Ga_2O_3 substrate (see Fig.2). The spoke wheel structure was etched at T_{sub}=800°C and TEGa flow rate of 12.1µmol/min to vertical etch depth of 2.5µm. In addition to vertical etching, lateral etching of the trenches was also observed, resulting in widening of the final trench widths. Using the final and initial trench widths, the ratio of lateral to a vertical etch rate was measured for various in-plane orientations on (010) β-Ga_2O_3. The lateral etch rate was found to be lowest for trenches oriented in the [001] direction (forms (100) sidewalls) and highest for fins oriented in the [102] directions (forms (-201) sidewalls). The trenches were also found to have vertical sidewalls which are ideal for fabricating sub-micron structures. The trench sidewalls along most orientations were found to be rough, however smooth sidewalls are obtained along [001] direction.

MD-TuP-6 Understanding Ohmic Contacts to N+ Doped (010) β-Ga_2O_3 by Both In-Situ MOCVD Doping and Silicon Ion Implantation*, Kathleen Smith,* *K. Gann, C. Gorsak, N. Pieczulewski, H. Nair, M. Thompson, D. Jena, H. Xing,* Cornell University

Despite the promising properties of β-Ga_2O_3 for kV radio frequency (RF) applications, such as the large bandgap and critical electric field, decent carrier mobility, and availability of native substrates via many melt-growth techniques, Ga_2O_3 faces similar challenges to many wide bandgap semiconductors. Namely, the low electron affinity associated with the wide bandgap leads to few low work-function metals to form ohmic metal-semiconductor junctions. Instead, Ga_2O_3 relies on tunnel junctions between a metal and heavily doped regions for ohmic behavior. However, the reliable formation of such junctions is non-trivial.

In order to enable high speed device applications, the parasitic resistance from the contacts R_c should be much less than 1 Ω-mm. In this work, we demonstrate ohmic contacts well below this threshold both for ion-implanted and metal-organic chemical vapor deposition (MOCVD) grown heavily doped (N_d > 1E19 cm^{-3}) Ga_2O_3. We also show the resultant R_c can depend on subtle differences in Ga_2O_3 surface properties.

Ion-implanted samples were prepared by implanting Si into a 400 nm unintentionally doped epitaxial layer grown on an Fe-doped (010) β-Ga_2O_3 substrate to a box concentration of 5x10^{19} cm^{-3} over 100 nm, activated by a 20 minute anneal at 950 °C in dry UHP nitrogen. Transfer length method (TLM) patterns were then formed with Ti/Al/Ni (50/100/60 nm) ohmic contacts. The contacts were then alloyed by a series of rapid thermal anneals (RTA) in nitrogen ambient. The resulting TLM patterns had an R_c of 0.16±0.01 Ω-mm, and a sheet resistance R_{sh} of 237±2 Ω/□.

Heavily doped samples were also grown on Fe-doped (010) β-Ga_2O_3 via MOCVD, with in situ Si doping to a nominal concentration of 9x10^{19} cm^{-3} and a thickness of 150 nm. TLM patterns were made with Ti/Au (50/110 nm) contacts, and compared before and after post-contact deposition RTA. On some MOCVD samples, the unalloyed contacts show an extremely leaky Schottky behavior, with a measured R_c of 0.35±0.002 Ω-mm and an R_{sh} of 55±1 Ω/□ at a current bias of 50 mA. On others, the unalloyed contacts show a highly rectifying behavior. These also become ohmic post annealing; however, the resultant contacts were found to be extremely non-uniform spatially. We currently ascribe these abnormal contacts to the formation of a spatially non-uniform interfacial layer on the Ga2O3 surface. While these results demonstrate the attainability of low R_c, future efforts will be needed to carefully control the surface properties to reliably achieve low R_c and apply these contacts to the moderately doped channels desired for kV RF applications.

MD-TuP-7 Heteroepitaxial Growth of $ZnGa_2O_4$ by Post-Deposition Annealing of ZnO on Ga_2O_3 Substrate*, Stefan Kosanovic,* *K. Sun,* University of Michigan, Ann Arbor*; U. Mishra,* University of California Santa Barbara*; E. Ahmadi,* University of Michigan, Ann Arbor

In recent years, β-Ga2O3 has attracted a great deal of interest for the next generation of power electronics due to its ultra-wide bandgap (~4.6 eV) and availability of native substrates. Spinel ZnGa2O4 is another ultra-wide bandgap semiconductor with similar bandgap (~4.6-5 eV) as Ga2O3. Moreover, in ternary spinel oxides, cations occupy octahedral and tetrahedral sites formed by oxygen atoms, leading to new possibilities for doping. Recent studies suggest that p-type doping in spinel ZnGa2O4 may be possible [1-3] Therefore, a Ga2O3-ZnGa2O4 heterostructure may enable design and fabrication of novel devices.

Several methods including sol-gel, RF magnetron sputtering, pulsed laser deposition, metalorganic chemical vapor deposition (MOCVD), and mist-CVD have been previously used for epitaxial growth of ZnGa2O4 on foreign substrates such as sapphire. Bulk ZnGa2O4 single crystal has also been fabricated using melt growth techniques [4]. Here we demonstrate a novel method for heteroepitaxial growth of high quality ZnGa2O3 on Ga2O3 substrate. In this method ZnO is first deposited by ALD on Ga¬2O3 followed by annealing at 900 C. TEM images revealed high structural quality of the film and a well-defined interface. SAED images showed that the ZnGa2O4 "semi-concurrently" matched to the Ga2O3 substrate, supporting high film quality. These results are demonstrated for the (-201), (001), and (010) Ga2O3 orientations.

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MD-TuP-8 Revitalizing Fractured β-Ga_2O_3 Nanomembranes: Nanogap Recovery for Enhanced Charge Transport Performance*, M. Hasan, J. Lai, Jung-Hun Seo,* University at Buffalo

A free-standing β-Ga_2O_3, also called β-Ga_2O_3 nanomembrane, is an important next-generation wide bandgap semiconductor that can be used for myriad high-performance future flexible electronics. However, details of structure-property relationships of β-Ga_2O_3 NM under strain conditions have not yet been investigated. In this presentation, we systematically investigated the electrical properties of β-Ga_2O_3 NM under different uniaxial strain conditions using various surface analysis methods and

revealed layer-delamination and fractures. The electrical characterization showed that the presence of nanometer-sized gaps between fractured pieces in β-Ga2O3 NM caused a severe property degradation due to higher resistance and uneven charge distribution in β-Ga_2O_3 NM which was also confirmed by the multiphysics simulation.

The degraded performance in β-Ga_2O_3 NM was substantially recovered by two different methods. (i) Saturated water vapor treatment: introducing excessive OH-bonds in fractured β-Ga_2O_3 NM via the water vapor treatment. The X-ray photoelectron spectroscopy study revealed that the formation of OH-bonds by the water vapor treatment chemically connected nano-gaps. (ii) Oxide passivation: deposition of a thin oxide layer such as Al_2O_3, HfO_2, and SiO_2 that is formed by an atomic layer deposition (ALD) system allows charges for hopping across fractured β-Ga_2O_3 pieces.

The treated β-Ga_2O_3 samples by the aforementioned method exhibited reliable and stable recovered electrical properties up to ~90 % of their initial values. Therefore, this result offers a viable route for utilizing β-Ga_2O_3 NMs as a next-generation material for a myriad of high-performance flexible electronics and optoelectronic applications.

MD-TuP-9 Impact of Magnetron Sputtered Ultra-Thin Layer of Fe-Doped β-Ga_2O_3 on Gallium Oxide Schottky Contacts, ***Adetayo Adedeji***, Elizabeth City State University; *J. Merrett,* Air Force Research Laboratory, Aerospace Systems Directorate*; J. Lawson, C. Ebbing,* University of Dayton Research Institute

Adetayo Victor Adedeji[1], Jacob Lawson[2], Charles Ebbing[2], J. Neil Merrett[3]

[1] Elizabeth City State University, [2] University of Dayton Research Institute, [3] Air Force Research Laboratory

Ultra-thin layer (~ 4 nm) of Fe-doped ß-Ga_2O_3 was deposited by co-sputtering pure Ga_2O_3 and Fe targets on (010) n+ Sn-doped Ga_2O_3 epilayer grown by Halide Vapor Phase Epitaxy (HVPE) on Si-doped ß-Ga_2O_3 substrates. The HVPE epilayer was about 4.5 mm thick and 2E16 cm^{-3} doping concentration. The ultra-thin insulating layer was deposited at 600°C substrate temperature for 10 minutes in Ar/O_2 gas mixtures (5% O_2 by flow rate). 100W RF power was applied to the Ga_2O_3 target while the dopant target was sputtered with 9W DC power. Circular Ti contacts were deposited on a 5 mm x 5 mm sample by photolithography and magnetron sputtering. The sample was annealed in argon flow at 400°C after contact metallization. The I-V characteristics of the Schottky diodes showed that the reverse current of samples with ultra-thin Fe-doped ß-Ga_2O_3 is more that five orders of magnitude lower than samples without the ultra-thin layer while the forward current dropped by about one order of magnitude. Appreciable forward bias tunneling current was achieved with much lower reverse current compared with samples without insulating nanolayer. It has been demonstrated that this technique can be used to tune the barrier height of Schottky contacts to ß-Ga_2O_3. Such low leakage contacts can be useful in improving the performance of metal-semiconductor gates in MESFETs or in reducing the edge leakage of Schottky power diodes.

MD-TuP-10 An Investigation of (001) β-Ga_2O_3 Etching via Heated H_3PO_4, ***Steve Rebollo***, *T. Itoh, S. Krishnamoorthy, J. Speck,* University of California, Santa Barbara

The fabrication of power devices that approach the β-Ga_2O_3 unipolar-FOM limit requires the use of field-management and RESURF techniques.[1] Utilizing dry etch processes for these techniques results in defect formation, which can impact the performance of devices.[2] Recently, Yuewei et al. used a wagon wheel pattern to explore the anisotropic etching behavior of (010) β-Ga_2O_3 in heated H_3PO_4. Compared to (010) β-Ga_2O_3, the (001) orientation is a better candidate for vertical power devices due to improved substrate scalability and slightly higher

PECVD was used to blanket deposit 533 nm of SiO_2 on Ga_2O_3. A wagon wheel pattern with 25 µm spoke widths was defined using photolithography. The spokes oriented along the [100] and [010] directions were carefully aligned to the edges of the substrates, which correspond to the (100) and (010) planes, respectively. Photoresist served as a mask to protect the SiO_2 during an HF etch. The SiO_2 etch rate was determined using Si substrates that were coloaded in the PECVD with the Ga_2O_3 substrate. Next, the sample was placed in a H_3PO_4/H_2O solution for 3.2 hours at a temperature of 140°C. The temperature was monitored and controlled using a temperature probe. The etch depth was determined via profilometry. Afterward, the sample was characterized via SEM.

Figure 1 shows an SEM image of the wagon wheel post-etch. The SiO_2 mask protecting the top of the spokes is still intact. Figure 2 shows a profile of the wagon wheel after etching. Assuming no significant SiO_2 etching[2], the (001) etch rate is 781 nm/hr. Figure 3 shows a 60°-tilted SEM image of a spoke oriented along the [-100] direction. An undercut of the SiO_2 mask can be observed. Since (010) is a mirror plane in β-Ga_2O_3, the spoke is symmetric about the (010) plane. Figure 4 shows the sidewall angles for the wagon wheel spokes. For spokes with an orientation in a positive k-direction, the right-hand sidewalls of the spokes were smooth and had low inclination angles and the left-hand sidewall exhibited roughness with a steeper inclination angle. The opposite was true for spokes oriented in the negative k-direction. This is another consequence of the mirror plane symmetry. The roughness could be the result of rough SiO_2 mask sidewalls. These findings can be useful for the development of dry-etch free process flows for high-performance devices.

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MD-TuP-11 An Organic, Direct Bonded Copper, Multi-Layered, Ultra-Low Inductance Package for High-Power UWBG MOSFETs, *J. Major, J. Calder, S. Zhao,* ***Faisal Khan***, National Renewable Energy Laboratory

The most common metalized substrates used in high-power switching packages consist of a ceramic layer such as Aluminum Nitride (AlN) sandwiched between two copper layers. Ceramic substrates are used because it has the key characteristic of having high dielectric strength while being thermally conductive. A large drawback to ceramic substrates is that they do not allow for a multi-layered circuit design. By replacing the traditional ceramic substrate with organic direct bonded copper (ODBC) we can open a wide range of possibilities when it comes to power module layout such as multi-layered circuits and double-sided cooling. Both benefits are critical while packaging high-performance Gallium Oxide (Ga_2O_3) MOSFETs. Because of Ga_2O_3's relatively poor thermal conductivity, a double-sided cooled package becomes necessary. Therefore, the use of ODBC provides the flexibility to fabricate copper traces carrying much higher currents, and by creating a multi-layered package, we can drastically reduce the parasitic inductance inside the power module. Achieving lower parasitic inductance is critical for an ultra-fast Ga_2O_3 package to avoid excessive voltage overshoot and ringing. Using ODBC, we have designed novel packages capable of handling the challenges presented by fast Ga_2O_3 switching. Using multi-physics modeling software, we can validate our design before building the prototype. Due to the simple process parameters needed to work with ODBC, we can rapidly create prototypes without using external vendors. This flexibility allows us to quickly design, build, and validate highly complex switching power modules to accommodate next generation, Ga_2O_3 switching devices.

Theory, Modeling and Simulation
Room Bansal Atrium - Session TM-TuP
Theory, Modeling and Simulation Poster Session

TM-TuP-1 Investigation of Oxygen Interstitial Diffusion Pathways in β-Ga2O3, ***Grace McKnight***, *C. Lee, E. Ertekin,* University of Illinois at Urbana-Champaign

Monoclinic β-Ga_2O_3 is a highly stable wide band gap semiconductor that exhibits a wide spectrum of complex defects. Understanding the diffusion of these defects may enable the precise optimization of the electronic and optical properties through controlled doping, making β-Ga_2O_3 a promising candidate for a diverse range of applications. While recent computational studies have investigated the diffusion of intrinsic defects including Ga interstitials and Ga and O vacancies as well as extrinsic defects like Si and Sn interstitials, the diffusion of O interstitials has received comparatively less attention. This is because, in many oxide semiconductors, O and H interstitials exhibit faster diffusion than other types of cation interstitials or vacancies, owing to their low diffusion barriers and small ionic sizes, thus making them highly mobile within the material. However, high anisotropy of the monoclinic crystal structure of β-Ga_2O_3 implies significant variations in the diffusion coefficients along different crystallographic directions. In this study, we aim to (1) understand the complete diffusion mechanism of oxygen interstitials and (2) predict directionality in diffusivity of oxygen interstitials in β-Ga_2O_3 from first principles calculations based on total energy density functional theory. We first explore all possible configurations

of oxygen interstitials and their formation energies including extended structures, such as O interstitials split into two or three O sites. We construct a diffusion network that includes every possible hop between each identified low-energy configuration and obtain the migration barriers by the nudged elastic band method. The migration paths and barriers of the diffusion network are used to construct and then solve the master diffusion equations, resulting in high anisotropy in Onsager transport coefficients, which illuminate the most dominant pathways in each crystallographic direction. Our study provides valuable insights into the migration of O interstitials, which contributes to the further developments and characterizations of β-Ga_2O_3 based applications.

TM-TuP-2 Optoelectronic Properties of $(In,Ga)_2O_3$ using First Principles Calculations, *E. Welch,* Prairie View A&M University*; P. Borges,* Federal University of Vicosa - Rio Paranaiba, Brazil*;* ***Luisa Scolfaro****, M. Talukder, R. Droopad,* Texas State University

Preliminary experimental results for In alloyed Ga_2O_3 ($In_{2x}Ga_{2-2x}O_3$) reveal these materials as to be promising for use as an n-type layer in a pn-junction with lattice matched, p-type materials like NiO [1]. This n-type conductivity is somewhat anomalous as In substitution/alloying alone is not expected to result in shallow defect states. O vacancies have been shown to exist in abundance in these materials but are known to not contribute to the conductivity as the compensating native defect formation in the material passivates these vacancies. Thus, a better understanding of point and complex defects are required to explain this behavior. Here, we studied In-based defects in Ga_2O_3 using hybrid density functional theory to understand potential sources of this n-type conductivity. The defects studied in Ga_2O_3 were single substitutional In (In_{Ga}), single interstitial In (In_i), and a defect complex comprised of a single In substitution and a single In interstitial (In_{Ga} + In_i). Formation energy calculations were used to quantify the stability of each defect where a negative value indicates relative stability. In_i can form during alloying of $(In_xGa_{1-x})_2O_3$ when the In content is low enough that individual In atoms settle into one of two Ga-O cages within the crystal; In interstitials are shown to prefer the larger Ga-O cage with an energy 1 eV lower than in the smaller cage. The In_i defect introduces 3 valence electrons which reside within the electronic band gap. This results in a partially filled band gap state which can be an intermediate transition state between the bulk electronic band edges. As the In content is elevated, In may become a substitutional defect at the cation site where octahedral O coordination is preferred over tetrahedral coordination; In is isoelectronic to Ga and is stable as a substitutional atom. The increase of In leads to substitution at higher content of In which leads to a reduction of the band gap and eventually to a phase transition, which is seen experimentally [2]. The In_{Ga}+ In_i complex defect can also occur, where the two defects can either be near one another (adjoined) or far in the crystal (disjointed). The formation energy for all systems in their neutral charge state except the single In substitution is positive and therefore these neutral defects are unstable. However, the prospect of polaron formation in the charged defect states indicates potentially stable defects with inter band gap states that may help to explain the anomalous n-type conductivity.

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[2] J. E. N. Swallow, et al., *ACS Appl. Mater. Interfaces* 13, 2807, **2021**.

TM-TuP-3 Modeling of β-$(Al_xGa_{1-x})_2O_3/Ga_2O_3$ High Electron Mobility Transistor (HEMT) and Current Aperture Vertical Electron Transistor (CAVET), ***Dawei Wang****, D. Herath Mudiyanselage, H. Fu,* Arizona State University

Due to its ultra-wide bandgap, high critical electric field, and large Baliga's figure of merit (FOM), beta-phase gallium oxide (β-Ga_2O_3) has attracted significant research attention for high-power, high-voltage, and high-frequency applications.

For the Ga2O3 HEMT simulation, the effects of delta-doping concentrations, width, and positions on the device performance, such as V_{TH}, transconductances, and breakdown voltages, were elucidated. Increasing delta-doping concentrations can reduce V_{TH} and improve transconductances due to larger 2DEG concentrations in the channel. However, it can also induce a parasitic leakage channel in the delta-doped region due to severe band bending of the conduction band and decrease the device breakdown voltages due to high electric fields at the gate edge. Varying the delta-doping concentrations resulted in a linear change in V_{TH}, which can be used as a reliable method to tune device V_{TH}. Closer delta-doping positions led to better channel quality and high transconductance of the devices. However, the delta-doped region should not be too close to the channel since it may extend into the channel, and degrade the electron mobility, impeding the high-frequency operation of the devices.

For the Ga2O3 CAVET, the conventional β-Ga_2O_3 CAVET showed concentrated electric fields under the gate with a low breakdown voltage (BV) of 260 V and a low peak electric field of 1.4 MV/cm, which is caused by insufficient gate control over the channel. For the introducing delta-doped β-$(Al_xGa_{1-x})_2O_3/Ga_2O_3$ heterostructure, it can reduce the R_{ON} due to the high density of 2DEG and suppress the OFF-state leakage due to the confined electron in the unintentionally doped channel layer. The OFF-state leakage from the aperture and CBL region in the β-Ga_2O_3 CAVETs was studied by simulation for the first time. A longer channel length can prevent the OFF-state leakage from the aperture but also increase the R_{ON} of HEMT-CAVETs. For small L_{ap} of <2 µm, the R_{Dep} became dominant in the R_{ON} due to the encroachment of the aperture by the depletion regions from the CBLs, while the R_{ap0} became dominant for large aperture lengths of >2 µm. For the breakdown simulation of the CBL region, the *BV* increased linearly with the thickness of the CBL increased. The peak electric field of β-Ga_2O_3 limit (~8 MV/cm) was obtained when the CBL layer increased to 6 µm. The *BV* of the CBL region increased linearly with the acceptor doping concentration. These results can serve as a critical reference for the future development of kV-class low R_{ON} β-Ga_2O_3 HEMT-CAVETs for high power, high voltage, high efficiency, and high-frequency applications.

TM-TuP-4 Electronic Band Structure and Excitons in $LiGaO_2$ and $LiGa_5O_8$, *N. Dadkhah,* Case Western Reserve University*; K. Dabsamut,* Kasetsart University, Thailand*;* ***Walter R. L. Lambrecht****,* Case Western Reserve University

Lithium gallate β-$LiGaO_2$ is mostly known as an optical insulator, but it may become an active ultra-wide-band-gap semiconductor by doping with Si, Ge [1]. Recently, we carried out studies of the band structure using the quasiparticle self-consistent (QS) *GW* method (*G* Green's function, *W* screened Coulomb interaction) [2,3] . Recent progress in the *GW* method allows us to include ladder-diagrams (electron-hole) interactions in the evaluation of the screening entering *W:* this method is here called QSGWΓ. Second, in the optical dielectric function, excitonic effects need to be included. We showed in [3] that the quasiparticle gap obtained in QSGWΓ is 7.0 eV, but electron-phonon coupling zero-point motion renormalization reduces it to 6.6 eV and excitonic effects are as large as 0.7 eV and lead to an exciton gap close to 6.0 eV, in excellent agreement with recent photoluminescence excitation and ellipsometry measurements [4]. The Bethe-Salpeter-Equation (BSE) calculations of the optical dielectric function reveal a modified Rydberg series of excitons, including dark excitons related to Wannier envelope functions that break the symmetry. The main luminescence bands were proposed in [4] to be donor-acceptor pair type. Using hybrid density functional defect pair calculations we identify the donor as Ga_{Li} and the acceptor as the Li vacancy and Li_{Ga} in the two observed DAP bands. Meanwhile it was found that CVD growth by Hongping Zhao's group (OSU) of Li-Ga-O films can lead to films with a composition of $LiGa_5O_8$. A compound with this composition is known to have a spinel type structure with Ga in both tetrahedral and octahedral sites. We have calculated its band structure in the QSGWΓ method to be 5.8 eV, while the BSE calculations indicate large exciton binding energy with an estimated lowest exciton or exciton gap at about 5.5 eV. Electron-phonon band gap renormalization is expected to lower these by ~0.3 eV.

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[4] L. Trinkler, A. Trukhin, B. Berzina, V. Korsaks, P. Šc

TM-TuP-5 Two–Dimensional Analytical Modeling of the Surface Potential of a Double–Gate Vertical Fin–Shaped Ga_2O_3 Power Transistor, ***Twisha Titirsha****, M. Hossain, M. Shuvo, Q. Huang, J. Gahl, S. Islam,* University of Missouri, Columbia

In recent years, the ultra-wide bandgap semiconductors, such as β-Ga_2O_3, have received significant attention owing to their ultra-wide bandgap (>4 eV), high breakdown strength (~8 MV cm^{-1}) and reasonable electron mobility (200-250 cm^2/Vs). The utilization of vertical Ga_2O_3 power devices presents new prospects in high-power applications. However, stable p-type doping in Ga_2O_3 remains challenging. Researchers expect FinFET structures to address this problem since these do not require p-type doping while designing on an n-type substrate. The dual-channel gating in vertical FinFET

yields a highly resilient control of gate electrostatics. In addition, handling high voltages through a thick drift layer minimizes the ungated access zone between the gate and the source, reducing the source resistance and resulting in high output currents and breakdown voltages. Vertical power devices can overcome the challenges associated with short-channel effects (SCE) in ultra-high density in integrated circuits and provide efficient carrier movement, and fast operational speed. Although highly relevant, the analytical model of the surface potential of fin-shaped vertical Ga_2O_3 powerFET has not been reported in the literature yet. This work presents a physics-based surface potential model for fin-shaped vertical Ga_2O_3 powerFET. The model reveals that variations in the doping concentration of Ga_2O_3 lead to distinct work functions, producing a channel potential profile resembling a step function-like profile which creates an additional peak in the electric field profile at the two junctions. The average velocity of the electrons in the channel rises due to this electric field peak, increasing the current value and strengthening the resistance to hot carrier leakage. Consequently, the reduction of the hot carrier effect leads to a significant increase in the breakdown voltage. Besides, the study indicates that the surface potential at the drain end exhibits a noteworthy increase compared to conventional lateral devices. In summary, this work highlights the improved carrier transport efficiency and SCE suppression of the fin-shaped vertical Ga_2O_3 powerFET device, demonstrating the potential applications in high-voltage and high temperature electronics.

Epitaxial Growth
Room Davis Hall 101 - Session EG+BG+MD-WeM

Epitaxial III

Moderators: Hari Nair, Cornell University, **Uttam Singisetti**, University of Buffalo, SUNY

9:15am **EG+BG+MD-WeM-4 Growth of α-$(Al_xGa_{1-x})_2O_3$ by Suboxide Molecular-Beam Epitaxy**, ***Jacob Steele***, *K. Azizie, N. Pieczulewski, J. McCandless, D. Muller, H. Xing, D. Jena,* Cornell University*; T. Onuma,* Kogakuin University, Japan*; D. Schlom,* Cornell University (USA) and Leibniz-Institut für Kristallzüchtung (Germany)

Ga_2O_3 has attracted significant interest due to its ultra-wide bandgap, high electron mobility, and large breakdown field. These properties exceed the current benchmarks set by materials such as SiC and GaN, making Ga_2O_3 optimal for next-generation power devices. Still, it has been proposed that the properties of Ga_2O_3 can be extended further by alloying with Al to form $(Al_xGa_{1-x})_2O_3$ which can raise the bandgap to 8.6 eV. This goal presents a challenge for the most researched phase, β, as β-Ga_2O_3 thermodynamically prefers a monoclinic structure and α-Al_2O_3 is stable in the corundum structure. This structural mismatch limits the compositional range and the range of attainable bandgaps. In contrast, α-Ga_2O_3 occupies the corundum structure and has been shown to alloy over the full compositional range, enabling bandgaps from 5.3 - 8.6 eV. One method of growing α-$(Al_xGa_{1-x})_2O_3$ is molecular-beam epitaxy (MBE). MBE is a powerful and highly controllable growth technique for α-$(Al_xGa_{1-x})_2O_3$ thin films with drawbacks being slow growth rates of a few hundred nm/h and narrow adsorption-controlled growth windows. One method to improve the growth rate is the technique of suboxide MBE, which allows growth of β-Ga_2O_3 thin films at rates exceeding 1 µm/h with large adsorption-controlled growth regimes.

We show that suboxide MBE can be used for the epitaxial growth of high quality α-$(Al_xGa_{1-x})_2O_3$ thin films on A plane sapphire substrates over the full range of x at greater than 1 µm/h. For our study, gallium suboxide, Ga_2O, and elemental Al are the MBE sources. The oxidant is 80% distilled ozone which is held at constant pressure (5 x 10-6 Torr) while the Ga_2O and Al fluxes are varied to control composition. We measure the composition of our films with XRD and confirm that we cover the full range of $0 < x < 1$ with vacuum ultraviolet transmittance measurements showing that the bandgaps of our films shift from α-Ga_2O_3 to α-Al_2O_3. We show that the film composition can be controlled directly by the relative ratios of the Ga_2O and Al fluxes. Our films have high structural quality as revealed by the full width at half maximum (FWHM) of rocking curves of the α-$(Al_xGa_{1-x})_2O_3$ films ranging from 11 - 15 arcseconds; these FWHMs are identical to the underlying sapphire substrates. The surfaces of the films are also smooth with RMS roughnesses measured by atomic force microscopy ranging from 0.3 - 1.1 nm on α-$(Al_xGa_{1-x})_2O_3$ films with thicknesses in the 17.8 - 47.8 nm range. We also show our progress with growing α-$(Al_xGa_{1-x})_2O_3$ films over 100 nm thick and with doping using a SiO_2 source.

9:30am **EG+BG+MD-WeM-5 Structural, Electrical, and Thermal Characterization of CIS-MOCVD β-Ga_2O_3 Epitaxial Buffer Layers**, ***Hannah Masten***, Naval Research Laboratory*; G. Alvarez,* Cornell University*; C. Halverson,* Washington State University*; M. Liao, J. Lundh,* Naval Research Laboratory*; F. Alema, A. Osinsky,* Agnitron Technology*; A. Jacobs,* Naval Research Laboratory*; M. Weber,* Washington State University*; Z. Tian,* Cornell University*; K. Hobart, M. Tadjer,* Naval Research Laboratory

Epitaxial growth of β-Ga_2O_3 using metalorganic chemical vapor deposition (MOCVD) has seen great advancements demonstrating high-quality films with low point defect concentrations and high mobility with low doping concentrations [1]. Here, we investigate the impact of buffer layer thickness for these MOCVD epitaxial films on electrical characteristics, thermal conductivity, and defect concentrations.

MOCVD films were grown on Novel Crystal Technology's Fe-doped (010) β-Ga_2O_3 substrates using Agnitron Technology's Agilis close-injection showerhead MOCVD (CIS-MOCVD). The unintentionally doped (UID) buffer layer thickness was varied on the 3 samples: A-300, B-500, and C-1000 nm. The UID layers were followed by a 10 nm thick n^+ (~10^{19} cm^{-3}) Ga_2O_3 layer for improved channel conductivity. A 100 nm highly n^+ layer was selectively regrown following ref. [2]. Ohmic contacts were formed in the regrown areas with an annealed 20/200 nm Ti/Au metal stack (470 °C, 1 min., N_2). Mesa isolation was formed with an etch of ~170 nm. Transmission line measurements (TLM) showed sample C had the lowest specific contact resistance of 2.25×10^{-6} Ω·cm^2 and sample A had the highest of 1.99×10^{-4} Ω·cm^2. Room temperature Hall effect measurement showed similar mobility for B and C of 115-116 cm^2/V·s, while sample A showed a much lower mobility of 71 cm^2/V·s. Samples B and C, both showed high open-gated source-drain current (I_D) (>0.05 A/mm at V_{DS}= 5 V) and low isolation (mesa-mesa) current (I_{iso}) of < 0.1 µA/mm at V_{DS}= 10 V. Sample A (300 nm thick buffer layer), showed 10X lower open-gated I_D and a high I_{iso} of ~3 mA/mm at V_{DS}= 10 V. Higher I_{iso} for samples with thin buffer layers, such as sample A, have been frequently attributed to a peak in Si concentration at the epilayer/substrate interface observed in secondary-ion mass spectroscopy [1]. Here, we offer further insight on this effect via frequency-domain thermoreflectance (FDTR) and positron annihilation spectroscopy (PAS). Preliminary FDTR data showed decreasing thermal conductivity for thicker epilayers. PAS data fitted with a 3-layer model consistently showed higher density of Ga-related vacancies in the epilayers compared to each substrate. More detailed measurements, including XRD and device-level FDTR, will be performed. This preliminary data suggested that MOCVD Ga_2O_3 was affected by both unintentional impurities and point defects in addition to the known issue of interfacial Si accumulation. [1] A. Waseem, *et al., Physica Status Solidi (*A), p. 2200616, 2022. [2] Z. Xia, *et al.,IEEE EDL*, 39(4), 568–571, 2018.

9:45am **EG+BG+MD-WeM-6 Electrical and Optical Properties of Melt-Grown Mn Doped β-Ga_2O_3**, ***Benjamin Dutton***, *C. Remple, J. Jesenovec,* Washington State University*; J. Varley, L. Voss,* Lawrence Livermore National Laboratory*; M. McCluskey, J. McCloy,* Washington State University

Several acceptor dopants have been explored in β-Ga_2O_3 to produce semi-insulating substrates and epitaxial films. Fe and Mg make up the majority of research thus far, however, other transition metals provide potential alternatives for optimized performance. β-Ga_2O_3 bulk single crystals were grown by the Czochralski and vertical gradient freeze methods with a nominal dopant concentration of 0.25 at.% Mn. Ultraviolet-visible-near infrared spectroscopy and photoluminescence revealed polarization and orientation dependent optical absorptions and a unique orange luminescence. All samples were electrically insulating, indicative of acceptor doping on the order of 10^9 – 10^{11} ohm·cm at room temperature. Actual dopant concentrations of the intentionally doped transition metal and background impurities were determined via glow discharge mass spectrometry, indicating the macro-scale segregation behavior. Laser-ablation inductively-coupled plasma mass spectrometry along with photoluminescence mapping revealed micro-scale segregation of impurity ions. Density functional theory calculations were carried out to elucidate likely site-occupancy and the acceptor level of Mn in the band gap.

10:00am **EG+BG+MD-WeM-7 Mg and Zn Counter doping of Homoepitaxial β-Ga_2O_3 Grown by Molecular Beam Epitaxy**, ***Stephen Schaefer***, *K. Egbo, S. Harvey, A. Zakutayev, B. Tellekamp,* National Renewable Energy Laboratory

Gallium oxide has attracted attention as a candidate material for high-power diodes and transistors owing to its wide bandgap and high breakdown voltage. Homoepitaxial β-Ga_2O_3 has been successfully grown by plasma-assisted molecular beam epitaxy, however it is well-documented that unintentional Si donors at the epitaxial interface lead to the formation of an undesirable parasitic conducting channel. Mg and Zn are deep acceptor levels in β-Ga_2O_3 and Mg counterdoping by MBE has been shown to compensate unintentional donor impurities. However counterdoping with other elements such as Zn remains sparsely investigated.

We report on Mg and Zn counterdoping in homoepitaxial β-Ga_2O_3 grown by MBE on (010) Fe-doped (semi-insulating) and (001) Sn-doped (n-type) wafers. A valved cracker source is used for Mg while Zn is evaporated from a conventional effusion cell. Mg- and Zn-doped stacks are measured by secondary ion mass spectroscopy to calibrate the cell temperatures and valve positions to the dopant incorporation. A typical Ga_2O_3 growth temperature is 600 °C and growth rates are 0.47 – 0.70 Å/s. β-Ga_2O_3 samples composed of a ~2 nm Mg- or Zn-doped layer and a 300 nm unintentionally doped layer are grown with dopant fluxes ranging from 3.8×10^{-9} to 2.0×10^{-8} torr. Counterdoped samples grown on (001) Sn-doped and (010) Fe-doped wafers are processed into vertical and lateral Schottky devices, respectively. In both devices the Ohmic contact is formed by stable 5 nm Ti / 100 nm Au annealed under N_2 at 550 °C while the Schottky contact is formed by 30 nm Ni / 100 nm Au. The Schottky devices are characterized by capacitance-voltage (C-V) measurements at 20 kHz.

We find that the C-V characteristics of the vertical Schottky devices grown on (001) Sn-doped Ga_2O_3 show a reduction in residual capacitance and corresponding increase in depletion width at high reverse bias voltage for the Mg-counterdoped sample compared to an undoped control sample grown under identical conditions. Additionally, the I-V characteristic of the Mg doped device exhibits lower reverse leakage current. These findings are

mirrored in lateral Schottky devices grown on (010) Fe-doped Ga_2O_3 where counterdoping with 1.0×10^{-8} torr Zn flux results in approximately ~2× reduction of capacitance and effective carrier concentration while counterdoping with the same Mg flux results in ~5× reduction. The C-V results suggest that Mg and Zn effectively compensate unintentional donors in Ga_2O_3. Experiments including an annealing study of Mg and Zn diffusion in β-Ga_2O_3 are expected to yield insight to the controllability of counterdoping in Ga_2O_3.

10:15am **EG+BG+MD-WeM-8 Optimizing Si Implantation and Annealing in β-Ga_2O_3, *Katie Gann,*** *N. Pieczulewski,* Cornell University*; T. Asel,* Air Force Research Laboratory*; C. Gorsak,* Cornell University*; K. Heinselman,* national renewable Energy Laboratory*; K. Smith, J. McCandless,* Cornell University*; B. Noesges,* Air Force Research Lab*; G. Xing, D. Jena, H. Nair, D. Muller, M. Thompson,* Cornell University

Optimizing the thermal anneal of Si implanted β-Ga_2O_3 is critical for low resistance contacts and selective area doping in advanced device structures. We report the impact of annealing time, temperature, and ambient on the activation of ion-implanted Si in β-Ga_2O_3 at concentrations from 5×10^{18} to 1×10^{20} cm^{-3}, and in β-$(Al_xGa_{1-x})_2O_3$ (x≤15%) at 5×10^{19} cm^{-3}. Nearly full activation (>90%) and high mobilities (>70 cm^2/V-s) are achieved in β-Ga_2O_3 with contact resistances below 0.16 Ω-mm. In β-$(Al_xGa_{1-x})_2O_3$, initial results are promising with moderate activation (50%) and high mobility (60 cm^2/V-s).

UID β-Ga_2O_3 films were grown by plasma assisted MBE on Fe-doped (010) β-Ga_2O_3 substrates; comparable β-$(Al_xGa_{1-x})_2O_3$ films were grown by MOCVD. Si was implanted at multiple energies to yield 65 or 100 nm box profiles with concentrations of 5×10^{18}, 5×10^{19}, or 1×10^{20} cm^{-3}. To understand damage accumulation, low and high temperature implants were also studied. Anneals were performed in a UHV-compatible quartz furnace at 1 bar with well-controlled gas ambients.

To maintain β-Ga_2O_3 stability, P_{O2} must be greater than 10^{-9} bar (based on annealing in vacuum or forming gas). For 5×10^{19} cm^{-3} Si, full activation is achieved for $P_{O2}<10^{-4}$ bar while 5×10^{18} cm^{-3} tolerates ~10^{-2} bar. Water vapor is critical even at 1 ppm; at 25 ppm active carriers are reduced by 10x. Optimal results were obtained with H_2O below 10 ppb. Based on recovery with subsequent "dry" anneals, we propose an OH-mediated defect compensating Si dopants.

Lattice recovery (mobility) occurs for T > 900 °C, with carriers and mobility increasing with temperature to 1050 °C. However, SIMS shows substantial Si diffusion above 1000 °C with 950 °C the optimal anneal temperature. Activation at 950 °C is maximized between 5 and 20 minutes with shorter times exhibiting slightly lower mobilities while longer times result in carrier deactivation; this "over-annealing" behavior occurs at all temperatures and becomes more significant at high concentrations. Room temperature implants to 1×10^{20} cm^{-3} are shown to fully activate under these optimal conditions.

To understand lattice damage recovery, implants at varying temperatures were characterized by XRD, Rutherford Backscattering Channeling (RBS/C), and STEM. XRD showed no second phases under any conditions. RBS/C and STEM showed only partial amorphization with remnant aligned β-Ga_2O_3. We propose a model to explain the efficient activation based on 3D lattice recovery in the absence of full amorphization.

Electronic and Photonic Devices, Circuits and Applications
Room Davis Hall 101 - Session EP+ET+MD-WeM

Process/Devices III

Moderator: Marko Tadjer, Naval Research Laboratory

10:45am **EP+ET+MD-WeM-10 Recent Progress of Ga_2O_3 Power Technology: Large-Area Devices, Packaging, and Applications*, Yuhao Zhang,*** Virginia Tech **INVITED**

The Ga_2O_3 power device technology has witnessed fast advances towards power electronics applications. Recently, reports on large-area (ampere-class) Ga_2O_3 power devices have emerged globally, and their scope has gone well beyond the bare-die device demonstration into the device packaging, circuit testing, and ruggedness evaluation. These results have placed Ga_2O_3 in a unique position as the only ultra-wide bandgap semiconductor reaching these indispensable milestones for power device development. This talk will review the state of the art of the ampere-class Ga_2O_3 power devices (current up to >100 A and voltage up to >2000 V), covering the following topics:

10. Static electrical performance of Ga_2O_3 diodes and MOSFETs with ampere-class demonstrations (Fig. 1), with a summary of their key parameters including breakdown voltage, on-state current, and specific on-resistance (Fig. 2).
11. Dynamic performance of large-area Ga_2O_3 diodes and MOSFETs, including the reverse recovery, switching charge, as well as turn-ON and turn-OFF characteristics. A large-area Ga_2O_3 diode with NiO junction termination extension will be analyzed as a case study (Fig. 3).
12. Packaging and thermal management of Ga_2O_3 devices, highlighting the global efforts on junction-side packaging and cooling to overcome the low thermal conductivity of Ga_2O_3 (Fig. 4).
13. Circuit-level applications of Ga_2O_3 power devices, such as PFC circuits and double-pulse tests, as well as their circuit-level overcurrent/overvoltage ruggedness.

These results of large-area Ga_2O_3 devices allow for a direct comparison with commercial Si, SiC, and GaN devices. Accordingly, research opportunities and critical gaps for Ga_2O_3 power devices will also be discussed.

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11:15am **EP+ET+MD-WeM-12 Forward and Reverse Current Transport of (001) β-Ga_2O_3 Schottky Barrier Diodes and TiO_2/β-Ga_2O_3 Heterojunction Diodes with Various Schottky Metals*, Nolan Hendricks,*** AFRL, UCSB*; E. Farzana,* UCSB*; A. Islam, D. Dryden, J. Williams,* Air Force Research Lab*; J. Speck,* UCSB*; A. Green,* Air Force Research Lab

β-Ga_2O_3 (BGO) has great potential for power devices due to its predicted breakdown field of 8 MV/cm, ease of n-type doping, and availability of melt-grown native substrates. The TiO_2/BGO heterojunction diode (HJD) has been shown to reduce reverse current compared to Schottky barrier diodes (SBDs) due to the high permittivity of TiO_2 without significantly affecting forward conduction losses due to the band alignment. [1] We demonstrate SBDs and HJDs with Ni, Pt, Cr, and Ti contacts, analyzing the current transport mechanism and showing similar or lower conduction losses in the HJD for all metals and reduced leakage current at higher electric fields in reverse bias.

SBDs and HJDs were fabricated on 8.5 µm of Si-doped BGO grown by HVPE on a Sn-doped (001) BGO substrate. Fabrication began with a backside Ti/Au cathode. 6.5 nm of TiO_2 was deposited on the HJD sample by plasma-enhanced ALD. Circular anode contacts (D=150 µm) of Pt/Au, Ni/Au, Cr/Au, and Ti/Au (20/180 nm) were patterned by separate lithography steps.

Capacitance-voltage (C-V) behavior was measured at 1 MHz. N_D-N_A and Φ_B were extracted from $1/C^2$. Current-voltage-temperature (J-V-T) characteristics of each device were measured, and Richardson plots were created from fitting the exponential region of each curve. Φ_B and the Richardson constant (A*) were extracted from each plot. Φ_B extracted for HJD is lower than in the SBD for Ni and Pt, while it is slightly higher for Cr. Unlike the Ti SBD, the Ti HJD showed rectifying behavior and exponential J-V in forward bias. Φ_B from C-V was similar but lower than J-V-T. In the linear-scale forward J-V characteristics at 25 °C, the lower Φ_B leads to lower V_{on}. No meaningful change in differential $R_{on,sp}$ is seen.

The reverse J-V behavior of each device at 25 °C was measured up to breakdown. To compare devices with different doping, J_R is plotted against the average electric field (E) at the BGO surface. In all cases, the HJDs saw

higher E_{bk} than the corresponding SBDs. At lower field, the leakage current is higher in devices with lower Φ_B as expected from thermionic emission. However, at higher field, the leakage current is lower in all HJDs than the corresponding SBDs, indicating suppression of thermionic field emission current due to the wider energy barrier in the HJD. More detailed analysis indicating TFE as the primary leakage mechanism will be shown. Sharp increases in reverse current associated with defect-mediated soft breakdown are not observed for the HJDs. The reduced forward and reverse losses with higher V_{bk} of the TiO_2/BGO HJD demonstrate its potential to unlock the benefits of BGO in power diodes.

11:30am **EP+ET+MD-WeM-13 Vertical β-Ga_2O_3 Diodes with PtO_x/Interlayer Pt Schottky Contact and High Permittivity Dielectric Field Plate for Low Loss and High Breakdown Voltage**, ***Esmat Farzana***, *S. Roy, S. Krishnamoorthy, J. Speck,* University of California Santa Barbara

β-Ga_2O_3 is promising for high-power devices due to a bandgap of 4.8 eV, high breakdown field of 8 MV/cm, melt-grown substrates and shallow donors. However, the breakdown of β-Ga_2O_3 Schottky barrier diode (SBD) is often dictated by tunneling leakage through metal Schottky contacts with a limited Schottky barrier height (SBH) of 1.5 eV. Although oxidized noble metals (e.g, PtO_x) with SBH>2 eV can reduce tunneling leakage and improve breakdown voltage, the trade-off comes with increased on-state loss. Here, we report an alternative scheme of composite Schottky contact, PtO_x/Interlayer Pt, as a solution of reducing leakage but minimizing turn-on loss compared to PtO_x. As shown with vertical GaN SBDs,[1] the sputtered PtO_x with an interlayer e-beam deposited Pt, can reduce leakage, increase breakdown voltage, while enabling low turn-on voltage. Moreover, for edge leakage management, we integrated high permittivity ZrO_2 field-plate in these SBDs.

The SBDs were fabricated on halide vapor phase epitaxy (HVPE) (001) β-Ga_2O_3 of 10 µm epitaxy (doping ~1×10^{16} cm^{-3}). Three different Schottky contacts were fabricated, Pt, PtO_x (24 nm)/Interlayer Pt (1.5 nm), and PtO_x (24 nm). The PtO_x/Interlayer Pt SBDs were also investigated with a field-plate dielectric of 100 nm ZrO_2 (dielectric constant~26) on top of a 11 nm Al_2O_3 formed by atomic layer deposition (ALD) to protect the surface from sputtering-induced damage.

In bare SBDs, the forward current density-voltage (J-V) provided near unity ideality factor and SBHs of Pt (1.1 eV), PtO_x/Interlayer Pt (1.49 eV) and PtO_x (1.90 eV). The $1/C^2$-V provided similar trend of SBH with Pt (1.48 eV), PtO_x/Interlayer Pt (1.92 eV) and PtO_x (2.28 eV). Thus, the interlayer Pt allows tuning of SBH to lower values than PtO_x, leading to lower turn-on loss. All SBDs showed punchthrough breakdown where the fully depleted condition is reached at -910 V (estimated). The bare PtO_x/Interlayer Pt SBDs showed lower leakage and higher breakdown voltage (V_{br}) of 1.76 kV compared to Pt with 1.32 kV. The ZrO_2 field-plate further increased V_{br} to 2.34 kV. With a minimum on-resistance of 8 mΩ-cm^2, the Baliga's figure-of-merit (BFOM) of the field-plate SBD was obtained as 0.684 GW/cm^2. SILVACO simulation showed a parallel plane peak field of 3.25 MV/cm at anode center, peak field of 8 MV/cm at edge in β-Ga_2O_3, and 8.86 MV/cm in Al_2O_3. The barrier height engineering and field management involving processing techniques with reduced or minimal material damage presented here is promising for realizing robust high performance β-Ga_2O_3 vertical power devices.

[1] Z. Shi et al., Semi. Sci. Tech. 37, 065010 (2022).

11:45am **EP+ET+MD-WeM-14 Ni/TiO_2/β-Ga_2O_3 Heterojunction Diodes with NiO Guard Ring Simultaneously Increasing Breakdown Voltage and Reducing Turn-on Voltage**, *J. Williams, N. Hendricks,* Air Force Research Lab; ***Weisong Wang***, Wright State University; *A. Adams,* Apex Micro Devices; *J. Piel, D. Dryden, K. Liddy,* Air Force Research Lab; *N. Sepelak,* KBR Inc.; *B. Morell,* Cornell University; *A. Miesle,* University of Dayton; *A. Islam, A. Green,* Air Force Research Lab

β-Ga_2O_3 is an ultra-wide bandgap semiconductor (~4.8 eV) with numerous merits that potentially surpass the material limits other semiconductors for power electronic applications, namely a high predicted critical field strength of 8 MV/cm. Vertical Schottky barrier diodes (SBD) are a fundamental application for β-Ga_2O_3 to demonstrate power handling capabilities. However, breakdown behavior is limited by electric field crowding at the contact edge and high tunneling current under large reverse bias. We are reporting a novel integration of vertical heterojunction diode based on Ni/TiO_2/β-Ga_2O_3 with p-type NiO as the guard ring (GR). The heterojunction improves off-state losses and breakdown voltage (V_{bk}) without adding significant on-state losses. Leakage current is reduced by the additional barrier width, but the negative conduction-band offset between TiO_2 and β-Ga_2O_3 maintains low V_{on}. P-type NiO guard ring is to surround heterojunction to screen the high electric field generated at this region.

The devices were fabricated on an 8.5 µm Si-doped β-Ga_2O_3 drift region grown by HVPE on a heavily Sn doped (001) substrate. A back-side Ohmic contact was formed by evaporated Ti/Au. The NiO GR was created by sputtering and lift-off. A thin TiO_2 layer (42 Å) by ALD was shaped to overlap the anode. The Ni/Au anode was deposited before mesa was etched to provide edge termination to the SBD and HJD. The devices have circular contacts (D=100 µm) with an additional 5 µm GR. SBDs were co-fabricated on the same substrate as references. HJD showed a lower V_{on} (0.8 V) than the SBD (1.1 V) from linear extrapolation of the J-V curve. Temperature dependent I-V behavior was measured from 25 ºC to 200 ºC. Both device types show excellent fits to the thermionic emission model, and barrier heights of 0.6 eV and 1.2 eV were fit for the HJD and SBD respectively. The HJD had higher V_{bk} of 1190 V compared to the SBD (685 V), and the GR HJD saw even further improvement with V_{bk} of 1777 V (826 V for GR SBD). The BFOM ($V_{bk}^2/R_{on,sp}$) of 518 MW/$cm^2$for the GR HJD is competitive with other literature results.

This work demonstrates an average breakdown field beyond the material limits of SiC and GaN in a device that has even lower conduction losses than the co-fabricated SBD. Lowering V_{on} while raising V_{bk} simultaneously improves both on- and off-state parameters that are typically in competition with each other. With further optimized field management, the Ni/TiO_2/β-Ga_2O_3-HJD presents a path to realistically utilizing the high critical field of Ga_2O_3 without large forward conduction losses from a high-barrier junction.

12:00pm **EP+ET+MD-WeM-15 Fabrication of Self Aligned β-Ga_2O_3 Junction Barrier Schottky Diodes with NiO Field Termination**, ***Joseph Spencer***, Naval Research Laboratory; *B. Wang, M. Xiao,* Virginia Tech; *A. Jacobs, T. Anderson, K. Hobart,* Naval Research Laboratory; *Y. Zhang,* Virginia Tech; *M. Tadjer,* Naval Research Laboratory

While the ultra-wide bandgap (4.8 eV) and the high critical field (6-8 MV/cm) of Ga_2O_3 is promising, the lack of shallow acceptors and the self-trapping of holes prevents this material from being doped p-type. The lack of complementary conductivity limits the practical device and termination structures for Ga_2O_3. Without the availability of p-type Ga_2O_3, Ga_2O_3 power devices must rely on a heterojunction for forming critically-important pn junctions. The naturally p-type nickel oxide (NiO, 3.6-4.5 eV [1]) forms a heterojunction with Ga_2O_3 and has been used to demonstrate Ga_2O_3 JBS diodes [2, 3].

In this work we have developed a self-aligned JBS diode fabrication process at 1 µm resolution that is capable of withstanding high-temperature thermal and chemical treatments such as annealing and relevant plasma/acid etches for Ga_2O_3 (e.g., BCl_3, HCl, H_3PO_4). This novel dry lift-off process incorporates a XeF_2 etch for undercut and lift-off steps producing a self-aligned process enabling fine device features without misalignment. A tri-layer mask consisting of, in order of deposition, amorphous Silicon (a-Si), SiO_2, and Ni, allow for the dry etching of the Ga_2O_3 epilayer prior to NiO self-aligned deposition. The Ni, SiO_2, and a-Si layers were patterned using Transene Ni-etchant, CF_4-plasma, and a SF_6-plasma dry etching, respectively. Subsequently, a ~250 nm deep trench in the Ga_2O_3 epilayer was etched via BCl_3 plasma, and a post-dry etch clean in warm (80 °C) H_3PO_4 was performed for 10 minutes, wherein the Ni hard mask was also removed. The a-Si mask layer was undercut using a 1" burst of dilute XeF_2 in a Xactix XeF_2 etcher. P-type NiO with 10% O_2 was sputtered (200 W, 12.5 mTorr) in the trench regions, followed by a dry lift-off of the remaining mask (a-Si/SiO_2) in XeF_2 gas by selective undercutting of the a-Si layer. At the conclusion of this self-aligned process, a tri-layer NiO junction termination extension (JTE) region was deposited around the anode perimeter in order to facilitate electric field spreading and improve V_{BR} [4]. Ni/Au anode was deposited atop the JBS region and the inner portions of the NiO JTE to conclude device fabrication (Figs. 1-4). Current-voltage characteristics in forward and reverse bias are shown in Figs. 5-6, respectively. This novel self-aligned process as shown by the fabrication of Ga_2O_3 NiOJBS diode serves to advance Ga_2O_3 heterojunction device technology and fabrication capabilities.

12:15pm **EP+ET+MD-WeM-16 Ni/$BaTiO_3$/β-Ga2O3 Solar-Blind UV Photodetectors with Deep Etch Edge Termination**, ***Nathan Wriedt***, *S. Rajan,* Ohio State University

We report on the design and demonstration Ni/$BaTiO_3$/β-Ga_2O_3 photodetectors, where high-permittivity $BaTiO_3$ is introduced to enable high fields approaching the material (avalanche breakdown) limit. β-Ga_2O_3 has a bandgap of 4.8eV and a corresponding photon absorption edge at

270-280nm, making it a prime candidate for utilization in solar blind UV photodetectors applications. Furthermore, the excellent material quality and low doping densities achievable through epitaxy on bulk-grown substrates can enable extremely low dark currents. Schottky diodes suffer breakdown well before the 8 MV/cm material limit. However, inserting the extreme-k $BaTiO_3$ dielectric between the metal and β-Ga_2O_3 prevents tunneling breakdown of the metal-semiconductor interface, and has been shown to support extremely high breakdown fields in β-Ga_2O_3 [1].When high electric fields occur in the β-Ga_2O_3 the electric field in the $BaTiO_3$ is low due to the relative permittivity, thus maintaining a tunneling barrier. Additionally, the valence band offset between the $BaTiO_3$ and Ga_2O_3 presents no barrier to transport of holes. Device were fabricated using (001)-oriented HVPE-grown Ga_2O_3 films (10-µm, N_d=1x10^{16} cm^{-3}) on Sn-doped Ga_2O_3 bulk substrates. The device structure investigated consisted of 1000 µm diameter circular mesas where the epitaxial layer was etched using a BCl_3/Cl_2-based ICP-RIE process to produce 0, 3, and 6-um pillars that have been shown to be effective in achieving high junction termination efficiency [2]. 10 nm $BaTiO_3$ was then deposited conformally by RF sputtering onto the etched surface. Device fabrication was completed by e-beam evaporation of Ti/Au backside ohmic contact and Ni top contacts. Extremely low dark currents (~0.25nA/cm^2) were measured under reverse bias up to 200 V. The devices showed an excellent UV/visible rejection ratio [R(244)/R(400)=3.65 *10^7]. We estimated the peak responsivity to be 970 mA/W at 244 nm at a reverse bias of -20 V. In conclusion, the work here shows the promise of Ni/$BaTiO_3$/β-Ga_2O_3 for realizing photodetectors with excellent operating characteristics. This work lays the foundation for future studies where the high breakdown strength enabled by $BaTiO_3$ could enable the design of solar-blind photodetectors with avalanche gain. We acknowledge funding from Department of Energy / National Nuclear Security Administration under Award Number(s) DE-NA0003921, and AFOSR GAME MURI (Award No. FA9550-18-1-0479, project manager Dr. Ali Sayir).[1] Xia et al, Appl. Phys. Lett. 115, 252104 (2019)[2]Dhara et al, Appl. Phys. Lett. 121, 203501 (2022)

12:30pm **EP+ET+MD-WeM-17 Best Paper Awards, e-Surveys, and Closing Remarks**,

Keynote Address
Room Davis Hall 101 - Session KEY-WeM

Keynote Address III

Moderators: Hari Nair, Cornell University, **Uttam Singisetti**, University of Buffalo, SUNY

8:30am **KEY-WeM-1 Welcome and Opening Remarks**,

8:45am **KEY-WeM-2 Gallium Oxide Microelectronics for Department of Air Force Applications**, ***Kelson Chabak***, Air Force Research Laboratory **INVITED**

The Department of Air Force (DAF) and DoD are pivoting to decentralized warfare to win future conflicts. The unique warfighting domains of the DAF require multi-function sensing that demand increased power in small volume platforms. Many of these domains have unique challenges such as no active cooling, temperature extremes, and radiation that require efficient wide and ultra-wide semiconductors. AFRL is a global leader in developing Gallium Oxide device technology for lateral and vertical power conversion with promising operation for switching applications. Further, we have found Gallium Oxide a robust high-temperature microelectronics technology. This presentation will highlight the above and other recent progress of AFRL to mature and transition Gallium Oxide for various RF and power switching applications.

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