Novel Materials
Room Ballroom A - Session NM-MoM1
Oxide Semiconductors

Moderator: Bharat Jalan, University of Minnesota

7:45am **NM-MoM1-1 Welcome and Sponsor Thank Yous,**

8:00am **NM-MoM1-2 Art Gossard MBE Innovator Awardee Talk: Setting a New Quality Standard for Both Holes and Electrons in GaAs Ultra-High Mobility Quantum Wells, *Loren N. Pfeiffer,*** Princeton University **INVITED**

8:30am **NM-MoM1-4 Silicon-doped *β*-Ga_2O_3 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,* Cornell University*; Z. Liu,* Penn State University*; M. Williams,* Clark Atlanta University*; K. Chabak,* Air Force Research Laboratory*; D. Muller,* Cornell University*; A. Neal, S. Mou,* 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 5x10^{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 2.7x10^{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.

8:45am **NM-MoM1-5 Improving Si Dopant Control 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

Ultra-wide band gap materials such as *β*-gallium oxide (*β*-Ga_2O_3) are promising for high power electronic devices since breakdown voltage scales with band gap. Within this material class, *β*-Ga_2O_3 is unique since *β*-Ga_2O_3 can be grown from the melt and demonstrates n-type conductivity with carrier concentration controllable between 10^{16} -10^{20} cm^{-3} with low donor activation energies.[1] However, oxidation of dopant material affects source vapor pressures which can impact dopant profile uniformity in *β*-Ga_2O_3 grown via PAMBE.[2,3] This work is focused 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 the thin films. SIMS and C-V measurements both show Si concentrations of ~3x10^{17} cm^{-3}. We also examine 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 and Si cell temperature on the background amount of Si present in *β*-Ga_2O_3 films.[4] In this work, we continued to explore sources of unintentional Si accumulation during the PAMBE growth process from sources like the quartz plasma bulb and Si effusion cell. 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 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, thus limiting the effectiveness of pre-growth surface treatments. Exposing a clean *β*-Ga_2O_3 surface to a quartz plasma bulb alone did not produce Si accumulation at the surface. On the other hand, a growth interrupt exposing a fresh *β*-Ga_2O_3 surface to a hot Si cell with shutter closed 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. These results point toward important challenges and potential solutions when growing Si-doped *β*-Ga_2O_3 thin films.

1 Neal, A. T. et al., *Appl. Phys. Lett.***113**, 062101 (2018).

2 Kalarickal, N.K., et al., *Appl. Phys. Lett.***115**, 152106 (2019).

3 McCandless, J.P., et al. *Appl. Phys. Lett.***121**, 072108 (2022).

4 Asel, T. J., et al., *J. Vac. Sci. Technol. A***38**, 043403 (2020).

9:00am **NM-MoM1-6 The Effect of Gallium Beam Flux on Electron Transoport 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

β-Ga_2O_3 has been of interest due to its large bandgap and high critical electric field, making it an excellent candidate for power electronic and RF applications [1]. The community has made significant improvements in the growth of *β*-Ga_2O_3 via several techniques including molecular beam epitaxy (MBE). However, there has not been a study of the relationship between the β-Ga_2O_3 growth parameters and their effects on the defects present in the crystal and their impact on the electronic transport properties. 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 difference based on the Ga beam. This is likely due to Ga vacancies that can form during desorption of Ga_2O during growth. These results indicate that there is significant impact on the electron transport properties of *β*-$Ga_{-2}O_3$ with a change in the Ga to O ratio during growth, and that optimization of growth parameters is needed to optimize the electronic properties of MBE grown *β*-$Ga_{-2}O_3$.

9:15am **NM-MoM1-7 Growth of α-$(Al_xGa_{1-x})_2O_3$ by Suboxide Molecular-Beam Epitaxy, *Jacob Steele,*** *K. Azizie, N. Pieczulewski, J. McCandless,* Cornell University*; I. Matara Kankanamge, M. D. Williams,* Clark Atlanta University*; H. Xing, D. Jena, D. Muller,* 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_3can 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_3thermodynamically 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 increase the growth rate is the technique of suboxide MBE, which allows growth of β-Ga_2O_3thin 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 our films.

9:30am **NM-MoM1-8 Electrostatic Gating of $SrSnO_3$ Thin Films with Improved Mobilities***, **Zhifei Yang**, F. Liu, T. Truttmann, B. Jalan,* University of Minnesota, USA

Ultra-wide-bandgap (UWBG) semiconducting oxides are becoming more crucial in sustainable technologies due to their promising use in applications including transparent electronics and power switching. Among them, alkaline earth stannates such as $SrSnO_3$ with the perovskite crystal structure have gained much interest in recent years. However, the room-temperature mobility of $SrSnO_3$ thin films has been shown to be limited by defective surface scattering. By using a 4 nm undoped $SrSnO_3$ capping layer on 19 nm La-doped $SrSnO_3$ thin film, the measured room temperature mobility has been shown to improve. In this structure, charge spill over from the doped layer to the undoped layer is expected to happen as Fermi levels equilibrate. Here, we demonstrate a reversible and electrostatic doping of $SrSnO_3$ thin films grown by Hybrid molecular beam epitaxy with tunable carrier densities using electric-double-layer transistor (EDLT) configuration with ion gels. Using modeling and a discrete two-channel model, we show that the modulation due to gating is confined within 4 nm at the top capping layer and the modulation leads to an increase of mobility in $SrSnO_3$ up to 130 $cm^2V^{-1}s^{-1}$ at 250 K. A detailed growth study combined with temperature-dependent Hall effect measurements and transport analysis will be presented.

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