Fundamentals and Technology of Multifunctional Materials and Devices
Room Golden West - Session C2-WeA
Novel Oxide Films for Active Devices

Moderators: Vanya Darakchieva, Linkoping University, Sweden, **Alyssa Mock**, Naval Research Laboratory

2:00pm **C2-WeA-1 The Physics of Low Symmetry Metal Oxides with Special Attention to Phonons, Plasmons and Excitons***, Alyssa Mock,* Linköping University, Sweden **INVITED**

We discuss the analysis of the dielectric function tensor for monoclinic metal oxides. We investigate the potential high-power device material gallium oxide and derive dispersions of transverse, longitudinal and plasmon coupled modes [M. Schubert *et al*., Phys. Rev. B 93, 125209 (1-18) (2016); Editors' Suggestion], the band-to-band transitions and excitons and their eigenvectors [A. Mock *et al*., Phys. Rev. B 96, 245205 (1-12) (2017)], the effective electron mass tensor using optical Hall effect measurements [S. Knight, A. Mock *et al*., Appl. Phys. Lett. 112, 012103 (2018); Editors' Pick], and the temperature dependence of band-to-band transitions energies [A. Mock *et al*., Appl. Phys. Lett. 112, 041905 (2018)]. We present the Lyddane-Sachs-Teller relation for monoclinic and triclinic semiconductors [M. Schubert, Phys. Rev. Lett. 117, 215502 (2016)]. We also discuss the identification of transverse and longitudinal phonons in scintillator material cadmium tungstate [A. Mock *et al*., Phys. Rev. B 95, 165202 (1-15) (2017)], and the dielectric and inverse dielectric tensor analysis method for transverse and longitudinal phonon mode dispersion characterization in high-power laser material yttrium orthosilicate [A. Mock *et al*., Phys. Rev. B, 97 165203 (1-17) (2018)]. Additionally, we discuss the application of these analysis techniques to triclinic single crystalline oligoclase. Further, we apply our methods to epilayers of beta-phase gallium oxide and discuss strain induced effects.

2:40pm **C2-WeA-3 Materials Interfaces for β-Ga_2O_3 Power Devices***, Rebecca L. Peterson,* University of Michigan, USA **INVITED**

Beta-phase gallium oxide (β-Ga_2O_3) is an ultra-wide bandgap semiconductor that holds great promise for future power electronics due to its ease of bulk crystal growth and facile ability to extrinsically dope *n*-type over a wide range of dopant concentrations. Power devices often operate at elevated temperature with large surge currents and high blocking voltages. Reliable operation under these aggressive conditions requires that the metal and dielectric interfaces, as well as the doping profiles within the device, be highly stable under thermal and electrical stress, including thermal cycling. Obtaining stable materials interfaces is a particular challenge for oxide semiconductors, due to the ready supply of oxygen within the bulk, and to thermodynamic competition amongst adjacent metal atoms to oxidize or reduce. This property has been exploited in other oxide devices, for instance in oxygen-vacancy based resistive memory (ReRAM). However such behavior must be strictly avoided in power devices to ensure reliable and stable operation.

In this talk, I will present our experimental investigations on the stability of dielectric and contact electrode interfaces to beta-phase gallium oxide, using comprehensive materials characterization and electrical measurements. We study novel dielectrics that can be used as gate insulators in field-effect transistors, and for field plates and passivation layers. We also investigate metal contacts to bulk Ga_2O_3 with a variety of dopants and doping levels, to determine pathways to form low-resistance and stable ohmic contacts. The experimental results will be compared to thermodynamic predictions based on Gibbs' free energies of reactions. Using these results, we will identify and discuss strategies for designing stable dielectric and contact interfaces in order to enable high-performance Ga_2O_3 power electronics.

3:20pm **C2-WeA-5 Phase Selectivity in Heteroepitaxial Ga_2O_3 Thin Films***, Virginia Wheeler, N Nepal,* U.S. Naval Research Laboratory, USA*; L Nyakiti,* Texas A&M University at Galveston, USA*; D Boris, S Walton, D Meyer, B Downey, C Eddy Jr.,* U.S. Naval Research Laboratory, USA **INVITED**

Ga_2O_3 has emerged as a promising material for next generation power electronics and UV photodetectors applications due to its large bandgap (4.9 eV) and the availability of affordable native substrates from melt-grown bulk crystals. While β-Ga_2O_3 (monoclinic) is the most stable and studied of five Ga_2O_3 polymorphs, the slightly less energetically favorable α- and ε-Ga_2O_3 phases have unique characteristics that can be exploited. The α -Ga_2O_3 (rhombohedral corundum) has the largest bandgap of 5.3 eV and can be alloyed with α-Al_2O_3 and α-In_2O_3 for bandgap engineering. T he ε-Ga_2O_3 phase (hexagonal wurtzite) is a polar phase, with a calculated polarization strength that is 10 and 3 times larger than that of GaN and AlN, respectively. Like the III-N system, polarization induced charges can lead to higher charge densities and mobilities in two-dimensional electron gases formed at heterojunctions, which would improve the viability of Ga_2O_3 electronic devices. In this work, we use atomic layer epitaxy (ALEp) to produce high-quality heteroepitaxial Ga_2O_3 films and investigate phase selectivity as a function of substrate type and orientation, growth temperature (T_g), plasma gas phase chemistry and gas pressure.

All ALE Ga_2O_3 films were deposited in a Veeco Fiji G2 reactor equipped with a load lock and turbo pump using trimethygallium and O_2 plasma precursors. Initial studies on c-plane sapphire substrates showed that decreasing chamber pressure an order of magnitude during the plasma step resulted in a shift from mostly ε-Ga_2O_3 to pure α-Ga_2O_3. Additionally, at 350°C and 8 mTorr, the phase could be altered by a varying the O_2 plasma flow from 5-100 sccm. Optical emission spectroscopy indicate that the ratio of O*/O2 is critical for phase selectivity while the high ion flux to the surface can contribute to the crystallinity at low T_g. By varying T_g from 300 to 500°C at 8 mTorr, films went from mixed β/ε phase at <350°C, to pure α-Ga_2O_3 at 350°C, to pure β-Ga_2O_3 at 500°C. Using the optimum growth conditions for α-Ga_2O_3 on c-sapphire, the influence of substrate was explored using a variety of substrates including AlN, GaN (bulk and epilayers), SiC, diamond, and Si. Deposition on III-N and β-Ga_2O_3 substrates all resulted in crystalline β- Ga_2O_3 films, while amorphous films were deposited on both SiC and Si. This suggests that a clean crystalline substrate interface is critical to obtaining high quality films and promoting metastable phases is more dependent on growth parameters than underlying crystal symmetry. Finally, we will discuss simple electrical properties of optimum films of each phase to validate feasibility of the process in device applications.

4:00pm **C2-WeA-7 Exfoliated β-Ga_2O_3 Nano-layer based (Opto)electronic Devices***, J Kim,* ***Sooyeoun Oh,*** Korea University, Republic of Korea **INVITED**

β-Ga_2O_3, which is a ultra-wide band-gap semiconductor (>4.8 eV at room temperature), is an attractive material for next-generation power electronics devices and solar-blind photodetectors. Owing to its ultra-high (theoretical) critical field strength of ~8 MV/cm, Baliga's figure of merit of β-Ga_2O_3 (at 3214) outperforms other wide bandgap semiconductors including SiC (at 317) and GaN (at 846), indicating that β-Ga_2O_3 offers a superior power switching capability. In β-Ga_2O_3 electronic devices, high breakdown voltage by using field plate structures has been demonstrated. In addition, a hetero-junction field-effect transistor by the integration with p-type semiconductor was reported. In β-Ga_2O_3 optoelectronic devices, various types of solar-blind (deep-UV) photodetectors have been demonstrated, including photoconductive-type, MSM-type, and Schottky barrier-type photodetectors. The details of the results will be presented at the ICMCTF2019.

4:40pm **C2-WeA-9 Towards Controlled Exfoliation of β-Ga_2O_3 through Ion Implantation***, Michael E. Liao, T Bai, Y Wang, M Goorsky,* UCLA, USA

β-Ga_2O_3 is a wide bandgap semiconductor that has the potential for high-power device applications. While heterostructures of thin film β-Ga_2O_3 grown on various materials such as GaN[1,2] and sapphire[3,4] have been reported, the understanding of direct wafer bonding β-Ga_2O_3 to form heterostructures is still limited. The benefits of wafer bonding β-Ga_2O_3 would be two-fold: (1) enables even more novel materials combinations to be realized and (2) other unprecedented orientations of β-Ga_2O_3 could be integrated with various materials. This last point is important for β-Ga_2O_3 due to its anisotropic properties especially since β-Ga_2O_3 exhibits the low-symmetry monoclinic crystal structure.

Currently there are reports of mechanically exfoliating β-Ga_2O_3 along cleavage planes parallel to the (100) and (001) planes.[5,6] However, this approach will be challenging to integrate in large-scale processing. Demonstrated with Si,[7,8] III-V's,[9-12] and CdZnTe,[13] the "SMART-Cut" method[14] is more compatible with large-scale processing. In this approach, ions are implanted in a handle substrate and subsequently annealed. Under the appropriate processing conditions, the implanted ions diffuse and agglomerate into bubbles during annealing and surface blistering, accompanied by exfoliation, can occur. In this work, (010) β-Ga_2O_3 substrates are implanted with hydrogen ions and subsequently annealed. Both high-resolution X-ray diffraction (XRD) measurements and transmission electron microscopy (TEM) images were employed to monitor the structural evolution with annealing. Symmetric ω:2θ XRD scans showed

that annealing at 150 °C and 300 °C did not change the implantation-induced strain appreciably; while annealing at 500 °C for 1 hour was sufficient in removing this strain. Additionally, TEM images showed subsurface hydrogen bubble formation. Despite implanting along a non-cleavage plane, ion implantation for exfoliation provides a promising pathway for obtaining thin layers of β-Ga_2O_3 with orientations other than (100) and (001).

References

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5:20pm **C2-WeA-11 Investigation on Microstructure and Piezoelectric Property of High Orientation Y-doped ZnO Thin Films via RF Magnetron Sputtering**, ***Li-Cheng Cheng***, *C Liu, J Huang,* National Cheng Kung University, Taiwan

In this study, we focused on the piezoelectric coefficients (d_{33}) depended on doping rare earth element, yttrium (Y), into ZnO thin films. Pure ZnO and Y doped ZnO (Y:ZnO) thin films with different yttrium contents were synthesized on p-type Si (111) substrates via RF magnetron sputtering, and the thickness of these thin films were fixed at 650 nm. In X-ray diffraction (XRD) patterns, Y:ZnO films with low yttrium contents (<3 at%) showed preferential orientation of (002) plane and still maintained columnar wurtzite structures. The positions of diffraction peaks shifted to lower angle as the concentration of yttrium increased due to the substitution of smaller host ions (Zn^{2+}: 0.74Å) by larger dopant ions (Y^{3+}: 1.04Å). When the concentration of yttrium is over 3 at%, the drastic transformation of morphology was observed in scanning electron microscopy (SEM) images, which consisted with the results of XRD analysis. This phenomenon caused by the lattice distortion, owing to the larger radii of Y^{3+} ions. The piezoelectric coefficients of pure ZnO and Y:ZnO thin films were measured by piezoresponse force microscopy (PFM) as well. The piezoelectric coefficients had achieved higher values (d_{33} ~ 86.8 pm/V) when the contents of yttrium was 3 at%, which compared to the theoretical values of pure ZnO thin films (d_{33} = 12.4 pm/V). Therefore, Y doped ZnO thin film was regarded as the promising candidate for piezoelectric nanogenerators (NGs).

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