Electronic Materials and Photonics Division
Room 304 - Session EM+MN+TF-ThM

Wide and Ultra Wide Band Gap Materials and Devices

Moderators: Erica Douglas, Sandia National Laboratories, **Rehan Kapadia**, University of Southern California, **Rachael Myers-Ward**, U.S. Naval Research Laboratory

8:00am **EM+MN+TF-ThM-1 What Can We Do With Ga_2O_3?**, ***Man Hoi Wong***, University of Massachusetts Lowell **INVITED**

The past few decades have witnessed technological innovations driven by physical electronics solutions embodying novel materials and device concepts that fundamentally change our lives today. Ultrawide-bandgap semiconductors represent a new area of intensive research covering a wide spectrum of materials, physics, devices, and applications. As the critical electric field of avalanche breakdown increases super-linearly with increasing bandgap energy, ultrawide-bandgap semiconductors can address critical needs across many areas including energy-efficient power switching, radio-frequency power, and electronics in harsh thermal or radiation environments. I will illustrate efforts to pursue these visions with Gallium Oxide (Ga_2O_3) devices, which have been making rapid strides thanks to ongoing breakthroughs in crystal growth and device processing technologies. Demonstrations of multi-kilovolt breakdown, normally-off operation, vertical device concepts, and heterostructures have positioned Ga_2O_3 devices as relevant contenders for practical applications. In this talk, the achievements on various types of Ga_2O_3 power switches and rectifiers will be reviewed. Materials science pertinent to the implementation of those device concepts will be highlighted. Several approaches to address challenges related to field management and doping will be discussed, using our recent work on enhancement-mode Ga_2O_3 power transistors as an illustration. We are also developing a novel Ga_2O_3 ultrahigh-speed transistor concept that harnesses quasi-ballistic transport effects through heterojunction engineering to reduce carrier transit delay. Such a device can simultaneously serve as an effective spectroscopy tool for studying hot-carrier dynamics in Ga_2O_3. This as well as other types of Ga_2O_3 quantum devices have seen scant experimental and theoretical developments to date and represent a fertile ground for research.

8:40am **EM+MN+TF-ThM-3 Controlled Growth of Epitaxial Ga_2O_3 Polymorphs for Ultra-Wide Bandgap Semiconductor Devices**, ***Lisa Porter***, *K. Jiang, J. Tang, M. Cabral, R. Davis,* Carnegie Mellon University, USA

Gallium oxide (Ga_2O_3) is attracting increased interest for electronics that can operate in extreme conditions, such as high power, high temperature and high radiation fluxes. This ultra-wide bandgap semiconductor has an interesting feature in that it exists in different phases, or polymorphs. β-Ga_2O_3 is thermodynamically stable at atmospheric conditions up to its melting point and is therefore the phase produced in melt-grown, single-crystal substrates.Epitaxial films of the other metastable polymorphs, however, are also of interest because they possess unique properties – such as high spontaneous polarization, ferroelectricity, or ferromagnetism – that could lead to new types of heterostructure devices.In this presentation we will summarize our results on the growth of epitaxial films of phase-pure vs. mixed-phase ε(κ), β, and γ-Ga_2O_3 using metal-organic chemical vapor deposition.We will focus on variables (temperature, triethylgallium (TEG) flow rate, and type of substrate) that have led to optimum control over the resulting polymorph and its microstructure, as characterized using x-ray diffraction (XRD), scanning electron microscopy, and high-resolution transmission electron microscopy (TEM).For example, for growth on (0001) sapphire substrates the phase composition of a 700-nm-thick epitaxial layer – from nominally 100% ε(κ) to 100% β-Ga_2O_3 – can be controlled by varying the substrate temperature (470 °C to 570 °C) and TEG flow rate (0.29 sccm to 2.1 sccm).We also show that nominally single-phase γ-Ga_2O_3 and β-Ga_2O_3 epitaxial films are produced under the same growth conditions (in the same growth run) by employing different substrates.High-resolution TEM and XRD ω-2θ and phi-scans suggest that the γ-Ga_2O_3 films are single crystal.

9:00am **EM+MN+TF-ThM-4 Plasma Enhanced-ALD Amorphous Gallium-Oxide Channel Thin Film Transistors for Back-End-of-Line Integration**, ***Charlotte Van Dijck***, Helmholtz-Zentrum -Berlin für Materialen und Energy, Germany; *F. Maudet,* Helmholtz-Zentrum-Berlin für materialen und Energy, Germany; *S. Banerjee, V. Deshpande, C. Dubourdieu,* Helmholtz-Zentrum Berlin für Materialen und Energy, Germany

Amorphous metal oxide semiconductors exhibit promising properties such as high mobility at low deposition temperatures (< 400°C) and hence are widely investigated as channel materials for thin film transistors (TFT). The low processing temperature also enables their integration on the back-end-of-line (BEOL) of Si CMOS circuits for More-than-Moore applications. While amorphous Indium Gallium Zinc Oxide (IGZO) and Indium Zinc Oxide (IZO) are the most studied amorphous metal oxides for TFT applications, amorphous gallium oxide (a-GaO_x) is interesting due to its ultrawide bandgap (~4.9 eV) combined with the ability to control the carrier density by varying the oxygen content in it [1]. Thus, a-GaO_x has potential for high voltage TFT, sensing, and memristive device applications. There have been few reports of a-GaO_x TFTs with pulsed laser deposition or solution processing, yet a detailed study of TFTs featuring ALD based a-GaO_x channel has not been reported up to now.

Here TFTs with a-GaO_x channel deposited with plasma-enhanced atomic layer deposition (PE-ALD) are discussed. PE-ALD allows for relatively low deposition temperatures (~ 250°C), uniform and conformal films. We recently showed that the current through the a-GaO_x layer can be increased with shorter O_2 plasma exposure times during PE-ALD as it increases the number of sub bandgap defects in the oxide [2]. We present a detailed study of a-GaO_x back-gated TFTs deposited with short (1s) O_2 plasma times to obtain a conductive channel. We discuss the main device characteristics such as subthreshold slope (SS), threshold voltage and ON current and their dependence on the a-GaO_x channel length and thickness (22, 50, 75 nm) with 20 nm ALD Al_2O_3 as gate oxide. Transistors with SS < 150 mV/dec and an ON/OFF ratio of 10^5 have been shown for a channel length of 6 µm. Impact of encapsulation of the GaO_x channel with in situ ALD-grown Al_2O_3 and ex situ PECVD-grown SiO_2 on the hysteresis in the transfer characteristics (drain current as a function of gate voltage) of the devices is investigated. A reduction of the hysteresis is achieved after in situ encapsulation of the devices with 2 nm Al_2O_3. Finally, the effect of post-metal annealing on the device performance is discussed.

[1] J. Kim et al. "Conversion of an ultra-wide bandgap amorphous oxide insulator to a semiconductor", NPG Asia Materials 9, e359 (2017)
[2] H. Kröncke et al., "Effect of O_2 plasma exposure time during atomic layer deposition of amorphous gallium oxide." Journal of Vacuum Science & Technology A 39, 052408 (2021)

9:20am **EM+MN+TF-ThM-5 Interface Trap State Analysis of ALD-deposited Gate Dielectrics on Gallium Nitride using a Modified *C*-ψ_s Procedure**, ***Brian Rummel***, *L. Yates, C. Glaser, A. Binder, J. Steinfeldt, T. Smith, P. Sharps,* Sandia National Laboratories; *J. Cooper,* Sonrisa Research; *R. Kaplar,* Sandia National Laboratories

The large breakdown electric field strength and high electron saturation velocity of gallium nitride (GaN) make it an attractive semiconductor for high-power and high-frequency applications. GaN-based power systems greatly exceed the power density capabilities of silicon-based systems and currently rival silicon-carbide-based (SiC) systems. However, GaN has been observed to have large interface trap densities at the gate dielectric/semiconductor interface, which inhibits channel mobility in contemporary MIS devices. In addition, typical gate dielectrics are usually deposited by atomic layer deposition (ALD) rather than being thermally grown due to a lack of a high-quality native oxide for GaN. ALD-deposited dielectrics are often associated with a higher concentration of charged oxide defects that promote significant gate leakage currents and induce large shifts in threshold voltages.

Mitigating these defects in wide band gap devices requires reliable characterization techniques suitable for large-scale device fabrication processes. Typical techniques used to characterize the density of interface states for gate dielectrics, such as the high-low method, require unconventionally large probing frequencies to account for fast trap states associated with wide-bandgap materials. The C-ψ_S technique is a quasi-static capacitance-voltage characterization method known for accurately determining surface potentials in MISCAP structures and has been rigorously demonstrated for SiC-based systems. For GaN systems, trap states located at the insulator/GaN interface or within the ALD-deposited dielectric may lead to dynamic charge/discharge processes that are less prevalent in SiC MIS structures with thermally grown oxides and thereby alter the C-ψ_S analysis. In this work, we successfully adapt the C-ψ_S analytical procedure to GaN-based MIS structures by imposing sensible mathematical conditions and accurately measure interface state densities and oxide charges for ALD-deposited gate dielectrics on n-GaN substrates. A range of post-deposition annealing temperatures is investigated to probe how processing conditions may alter defect states associated with alumina or silicon dioxide gate dielectrics. This work highlights recent progress in our endeavor to fabricate robust GaN-based high-power devices and establish reliable wide-bandgap device characterization procedures.

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9:40am **EM+MN+TF-ThM-6 Characterization of Intervalence Band (IVB) Transitions in Boron-Doped Diamond***, **Souvik Bhattacharya**,* University of Illinois at Urbana Champaign*; J. Boyd,* Case Western Reserve University*; A. Hossein, S. Reichardt,* University of Luxembourg*; N. Maccaferri,* Umea University, Sweden*; O. Shenderova,* Adamas Nanotechnologies Inc.*; L. Wirtz,* University of Luxembourg*; M. Sankaran,* University of Illinois at Urbana Champaign*; G. Strangi,* Case Western Reserve University

Heavily-doped semiconductors are a special class of materials distinct from both their metal and semiconductor counterparts that can exhibit greatly enhanced electrical conductivity[1] and tunable localized surface plasmon resonances (LSPR)[2, 3]. For example, boron-doped diamond is a wide band-gap, p-type semiconductor which has elicited interest for quantum computing[4] and superconductivity[5]. Here, we characterized boron-doped diamond (BDD) powders by valence electron-energy loss spectroscopy (VEELS) using a scanning transmission electron microscope to reveal potentially new electronic transitions within the valence band. The diamond samples were synthesized commercially by high-pressure-high-temperature (HPHT) methods and obtained from Adamas Nanotechnologies. Basic materials characterization such as high-resolution transmission electron microscopy (HR-TEM), core-EELS and micro-Raman spectroscopy were conducted to assess the structure and crystallinity. The boron doping level was determined to be ca. 800 pm by modelling the Fano line shape and shifts of the zone center peak at 1332 cm-1. The majority of our study then focused on the low-loss region of EELS (i.e., VEELS) where we observed an intense and relatively broad signal on the shoulder of the zero-loss peak (ZLP) that was completely absent in a similarly synthesized undoped (intrinsic) diamond sample. The feature was found to vary spatially within the body of each particle and inferred to correlate with the distribution of boron atoms along the diamond crystal planes. Ab-initio calculations were carried out in support of the experiments to calculate the loss function from the dielectric function. We find that intervalence band transitions of valence band electrons can lead to the observed VEELS features, and that these transitions can couple to form a "plasmon-like" excitation.

References:

1.J. Zhou, H. Zhu, Q. Song, Z. Ding, J. Mao, Z. Ren and G. Chen, Nature Communications 13 (1), 2482 (2022).

2.J. A. Faucheaux, A. L. D. Stanton and P. K. Jain, The Journal of Physical Chemistry Letters 5 (6), 976-985 (2014).

3.Z. Liu, Y. Zhong, I. Shafei, R. Borman, S. Jeong, J. Chen, Y. Losovyj, X. Gao, N. Li, Y. Du, E. Sarnello, T. Li, D. Su, W. Ma and X. Ye, Nature Communications 10 (1), 1394 (2019).

4.P. de Leon Nathalie, M. Itoh Kohei, D. Kim, K. Mehta Karan, E. Northup Tracy, H. Paik, B. S. Palmer, N. Samarth, S. Sangtawesin and D. W. Steuerman, Science 372 (6539), eabb2823 (2021).

5.T. Yokoya, T. Nakamura, T. Matsushita, T. Muro, Y. Takano, M. Nagao, T. Takenouchi, H. Kawarada and T. Oguchi, Nature 438 (7068), 647-650 (2005).

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