Thin Films Division
Room 316 - Session TF2+EM-FrM

Wide and Ultra-Wide Bandgap Thin Films: Advances in Deposition and Novel Materials

Moderators: Christophe Vallee, SUNY College of Nanoscale Science and Engineering, **Virginia Wheeler**, U.S. Naval Research Laboratory

10:00am **TF2+EM-FrM-6 AlGaN, An Enabling Ultra-Wide Bandgap Semiconductor**, ***Dolar Khachariya,*** Adroit Materials*; M. Breckenridge, D. Szymanski, S. Stein,* North Carolina State University*; W. Mecouch,* Adroit Materials*; Y. Guan, P. Bagheri, S. Rathkanthiwar,* North Carolina State University*; P. Reddy, R. Kirste, S. Mita, B. Moody, J. Tweedie,* Adroit Materials*; K. Sierakowski, M. Boćkowski,* Institute of High-Pressure Physics, Poland*; E. Kohn, S. Pavlidis, R. Collazo, Z. Sitar,* North Carolina State University **INVITED**

III-nitride ultra-wide bandgap semiconductors offer a future alternative to maintain the growing demand for high-power devices. Current III-nitride devices already offer higher breakdown voltages (BV) and reduced on-resistances (R_{ON}) compared to Si and SiC. However, several power devices, such as junction barrier Schottky (JBS) diodes and superjunctions (SJ), which provide an improved BV and R_{ON} tradeoff, have not been demonstrated in III-nitrides. The major limitation is the difficulty of achieving selective area doping. In the JBS diode, p-regions must be laterally interspersed between n-regions below the anode contact. A SJ device requires alternating lateral n- and p-type doping regions with zero net charges. Two approaches can be considered to address this challenge: ion implantation and polarity control.

Currently, III-nitrides do not possess a robust ion implantation toolbox that allows for reliable implantation control and activation. Recent advances in ion implantation for the realization of n-type AlN and p-type GaN will be discussed. For n-type AlN, Si implantation was realized with the implementation of defect quasi-Fermi level control. The highest *n*-type conductivity in AlN will be demonstrated. For p-type GaN, we demonstrate the ability to successfully achieve *p*-type conductivity via Mg implantation and post-implantation annealing at ultra-high pressure. Using this technique, GaN JBS diode with low R_{ON} and high BV will be discussed.

The inherent polar doping selectivity of GaN can be used to achieve the doping scheme for a lateral GaN p/n junction. Oxygen, which unintentionally incorporates into N-polar GaN, acts as the n-type dopant, whereas Ga-polar GaN does not readily incorporate oxygen and remains undoped. Accordingly, lateral polarity junctions (LPJs) with alternating domains of O-doped N-polar and Mg-doped Ga-polar GaN have been fabricated to realize lateral p/n junctions. For drift regions, the n-type doping in the N-polar domain (and p-type doping in the Ga-polar domain) was reduced to ~10^{17} cm^{-3}. Implementing the chemical potential control (CPC) framework and supersaturation modulated growth (SMG), a GaN LPJ with a smooth surface and equal domain heights with the necessary doping profile will be discussed.

10:40am **TF2+EM-FrM-8 CVD of Crystalline and Amorphous sp^2-BN Thin Films on Different Orientations of Al_2O_3**, *S. Sharma,* Linköping Univ., IFM, Thin Film Physics Div., Sweden*;* ***Laurent Souqui,*** University of Illinois at Urbana-Champaign*; H. Pedersen,* Linköping University, IFM, Sweden*; H. Högberg,* Linköping Univ., IFM, Thin Film Physics Div., Sweden

Thin films of epitaxially grown sp^2-hybridized boron nitride (sp^2-BN) in its hexagonal (h-BN) and rhombohedral (r-BN) phases have potential applications in optoelectronics and graphene technologies. Additionally, amorphous sp^2-BN (a-BN) is a promising material for electronic applications as a dielectric along with being a barrier for metal diffusion. Thin film growth of sp^2-BN is typically done using chemical vapor deposition (CVD). Growth of epitaxial sp^2-BN thin films requires high growth temperatures, above 1200 °C; for this reason, (0001) oriented sapphire (Al_2O_3) substrates are commonly used. Our study[1] investigates the growth of sp^2-BN using thermal CVD, comparing the differences in growth on Al_2O_3(11-20), Al_2O_3(1-102), Al_2O_3(10-10) and Al_2O_3 (0001), known as *a*-cut, *r*-cut, *m*-cut and *c*-cut substrates respectively, with an AlN buffer layer. For growth of sp^2-BN on these cuts, we use two boron precursors triethylborane (TEB) and trimethylborane (TMB), both along with NH_3 to investigate different chemical pathways.

Regardless of the boron precursor used, sp^2-BN growth on all the substrates was confirmed using Fourier transform infrared spectroscopy. X-ray Diffraction (XRD) 2θ/ω scans revealed that the sp^2-BN films grown on *c*-cut and *a*-cut were crystalline with the basal planes parallel to the substrate surface, while sp^2-BN films deposited on *r*-cut and *m*-cut were X-ray amorphous. XRD ϕ-scans showed the epitaxial growth of r-BN on *c*-cut and *a*-cut substrates. The in-plane relationship on the *a*-cut is r-BN[11-20]‖ w-AlN[11-20]‖ α-Al_2O_3[0001], which is similar to the *c*-cut. Using XRD ω-scan on the r-BN0003 peak, we determined that the crystal quality of r-BN is higher on the *a*-cut compared to the *c*-cut substrate; full width half maximum of 0.98° and 1.15° respectively. Scanning electron microscopy showed triangular shaped grains surrounded by less ordered material on the surface for the *c*-cut and *a*-cut while no such triangular features were seen on the *r*-cut and *m*-cut substrates. Our results show that epitaxial r-BN films are grown with determined in-plane orientations and with higher crystal quality on the *a*-cut. Conversely, a-BN films can be grown using the *r*-cut and *m*-cut substrates.

To advance the field, we will apply advanced analytical microscopy to study the differences locally, in terms of crystallinity, chemical bonding, and the influence of carbon in our deposited films. Additionally, other aspects of amorphous growth will be investigated.

(1) Sharma, S et al. Chemical Vapor Deposition of Sp^2 -Boron Nitride Films on Al_2O_3 (0001),(11-20),(1-102),and(10-10) substrates . *J. Vac. Sci. Technol. A* **2022**,*40*(3),033404

11:00am **TF2+EM-FrM-9 Investigating SiC/Graphene/SiC(0001) Remote Epitaxy Using Hot-wall CVD**, ***Daniel J. Pennachio,*** US Naval Research Laboratory*; J. Hajzus,* ASEE Postdoctoral Fellow at US Naval Research Laboratory*; A. Lang,* US Naval Research Laboratory*; R. Stroud,* Former employee of US Naval Research Laboratory*; R. Myers-Ward,* US Naval Research Laboratory

Remote epitaxy (RE) is a promising new technique for epitaxial film removal and substrate reuse that utilizes monolayer graphene as a release layer [1]. Graphene grown directly on SiC(0001) substrates through Si sublimation or through propane chemical vapor deposition (CVD) is an ideal platform for remote epitaxy of wide bandgap (WBG) semiconductors as there is no need for a graphene transfer step, reducing the risk of introducing contamination or defects that can complicate the study of the remote epitaxy process. In addition, this materials system is compatible with commercially-viable WBG semiconductor growth and processing. However, SiC CVD growth is typically conducted using high-temperature hydrogen-based chemistries that could damage or remove graphene. This study investigates the effect of alternate CVD growth conditions on SiC/graphene/SiC(0001) remote epitaxy and optimizes CVD parameters to produce high-quality SiC epilayers while reducing damage to the graphene barrier. In addition, since the effect of epitaxial graphene features such as SiC macrostep morphology and associated layer inhomogeneity on the RE process is currently unknown, graphene preparation and associated morphology is varied to explore its effect on SiC epilayer formation.

Semi-insulating nominally on-axis 6H-SiC(0001) and n-type 4° off-axis 4H-SiC(0001) substrates were used to produce different SiC surface morphologies and graphene layer numbers. Ar:H_2 process gas flow ratio, growth precursor C/Si ratio, and growth temperature were optimized during hot-wall CVD RE to promote smooth film morphology. Nomarski optical microscopy, scanning electron microscopy, and atomic force microscopy found CVD deposition at 1620°C with Ar/H_2 ratios <20/5 slm, and C/Si ratios <1.55 to have the smoothest surface morphology and fewest polytype inclusions. Substrates with offcuts <0.1° from SiC(0001) exhibited lower epilayer macrostep density, but showed evidence of polytype impurities and 3D growth at C/Si ratios > 1.0. Point defect density in RE SiC epilayers using a graphene interface was shown to be lower than SiC homoepitaxy using similar conditions without graphene. Cross-sectional transmission electron microscopy was utilized to assess the growth interface and graphene layer integrity after CVD growth. Through this study, optimal RE growth processes are suggested for a balance of graphene survivability and SiC film morphology.

[1] Kim, Y., Cruz, S., Lee, K. *et al. Nature* **544,** 340–343 (2017).

11:20am **TF2+EM-FrM-10 Sputter Deposition of III-N Thin Films**, ***Joshua Nordlander,*** The Pennsylvania State University*; Z. Sitar,* North Carolina State University*; J. Maria,* The Pennsylvania State University

In this presentation, we demonstrate that reactive High-Power Impulse Magnetron Sputtering (HiPIMS) is an effective alternative for depositing high quality, epitaxial III-N thin films. In contrast to conventional direct current (DC) sputtering, HiPIMS provides the needed kinetic energy and ionization fraction to establish a sufficiently reactive environment to promote full nitridation.Specifically, the low duty cycle regime of HiPIMS provides access to kW/cm^2 peak power densities without target

degradation and thus dramatically increased metal reactivity. In addition, adding an opposite polarity voltage pulse between the target bombarding events, known as a kick pulse, further allows one to tailor both the adatom landing energy on the substrate surface, and mitigate target poisoning.

This unique capability set enables us to prepare high crystal quality epitaxial InN thin films with low out-of-plane mosaicity and electron mobilities in excess of 400 cm^2/Vs with a step-and-terrace microstructure when deposited on AlN-nucleated sapphire substrates.Equilibrium supersaturation models are useful for predicting the surface microstructure of these films by varying the V/III ratio or deposition temperature.

In addition, homoepitaxial GaN thin films can be deposited at temperatures below 600°C with smooth surface morphologies characterized by c/2 steps and terraces.The presentation will focus on the relationships between sputtering parameters and III-N thin film crystal quality, surface morphology, and growth rate.

11:40am **TF2+EM-FrM-11 Thickness Dependent Properties of Ferroelectric Boron-Substituted Aluminum Nitride Thin Films***, **John Hayden**, J. Nordlander, W. Zhu, S. Trolier-McKinstry, J. Maria,* Pennsylvania State University

Recently discovered wurtzite structured ferroelectrics are interesting as next generation materials for ferroelectric memory devices, however they suffer from large leakage currents at small film thicknesses. In this work, we investigate the thickness dependent properties of ferroelectric boron-substituted aluminum nitride based thin films deposited by magnetron co-sputtering. Films grown on tungsten coated sapphire substrates show robust ferroelectricity for thicknesses as small as ~100 nm. Polarization hysteresis measurements of films thinner than 100 nm show inflated remanent polarization values from leakage currents. Electron microscopy studies and thickness dependent x-ray rocking curve measurements indicate there is a defect rich region near the film-electrode interface with reduced film crystallinity and out-of-plane mosaicity. In an attempt to improve film quality near the interface, films are grown on a variety of electrode materials with varying chemical and structural similarities to wurtzite structured aluminum nitride. Tungsten nitride is chosen as it is nitrogen containing, yet structurally dissimilar to aluminum nitride, while indium nitride is chosen because it is isostructural to aluminum nitride. For films grown on tungsten nitride, roughness and leakage currents decreased with decreasing electrode thickness, though no substantial improvements compared to films grown on W were observed. Films grown on epitaxial indium nitride/aluminum nitride/sapphire stacks adopt the stepped surface morphology of the InN and exhibit significantly narrower rocking curve widths compared with films grown on W. Film crystallinity, leakage current, and ferroelectric properties are investigated as a function of indium nitride surface morphology and ferroelectric film thickness.

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