Chemical Analysis and Imaging of Interfaces
Room 121 - Session CA-FrM

Materials, Interfaces and Metrologies for Electronics

Moderators: Alex Belianinov, Sandia National Laboratory, **Andrei Kolmakov**, National Institute of Standards and Technology (NIST)

8:15am **CA-FrM-1 Surface Transfer - Modulation Doping at the Diamond-Dielectric Interface***, A. Deshmukh, Y. Yang, F. Koeck, R. Nemanich,* ***Kevin Hatch,*** Arizona State University **INVITED**

Great progress in diamond wafer technology and diamond epitaxy have inspired new concepts for diamond electronics particularly for power conversion and RF applications.However, the highactivation energy of substitutional p- and n-type dopants in diamond has limited the development of field effect transistors (FET). An alternative approach of charge transfer doping at a diamond-dielectric interface, which results in the formation of a hole accumulation layer, is not limited by thermal activation [1].However, the hole transport shows a mobility that is much lower than predicted. It is widely accepted that the low mobility is due to scattering from the near interface negative charges transferred into the dielectric layer.

Following the concept of modulation doping at heterostructure interfaces, we have proposed and demonstrated a dielectric layer configuration that results in a nearly ten-fold mobility increase for the accumulated holes at the diamond interface [2]. In this approach MoO_3 is used as the charge transfer dielectric, and Al_2O_3 is employed as the modulation doping spacer layer. The charge transfer is driven by the energy difference between the diamond valence band and the charge transfer states in the MoO_3. The thickness of the spacer layer also affects the hole accumulation layer charge density.

In this study photoemission spectroscopy is employed to measure the band alignment and band bending throughout the multi -layer structure.The relative distribution of the charge near the interface is deduced from the band diagram. These experiments and the model of Surface Transfer - Modulation Doping demonstrates a new approach to FET channel doping for diamond field effect transistors.

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[1]K. G. Crawford, I. Maini, D. A. Macdonald, and D. A. J. Moran, “Surface transfer doping of diamond: A review,” Prog. Surf. Sci. 96, 100613 (2021).

[2]Yu Yang, Franz A. Koeck, Xingye Wang, and Robert J. Nemanich “Surface transfer doping of MoO3 on hydrogen terminated diamond with an Al2O3 interfacial layer,” Appl. Phys. Lett. 120, 191602 (2022).

8:45am **CA-FrM-3 Probing the Nanoscale: The Synergy of XPS and LEIS Analyses***,* ***Joshua W. Pinder****, J. Crossman,* Brigham Young University*; S. Prusa, T. Sikola,* Brno Institute of Technology, Czechia*; M. Linford,* Brigham Young University

Over the past few decades, with the development of novel, advanced materials, the significance and need for surface characterization techniques has increased dramatically. These advanced materials appear in diverse sectors of the economy including in semiconductors, thin films, catalysts, batteries, fuel cells, adhesion, and for material durability. An understanding of surface and material composition often leads to improvements in material properties. In this talk, we discuss the synergy and usefulness of two important surface techniques: X-ray photoelectron spectroscopy (XPS) and low energy ion scattering (LEIS).

XPS is a mature and well-developed technique, providing both elemental and chemical state information about surfaces. However, XPS spectra do not always unambiguously identify the depths of atoms at surfaces. It is not always clear whether an atom is exposed at a surface or slightly below it. Whether an atom is exposed or not has profound implications in various fields, including in catalysis. Accordingly, LEIS, which is sensitive to the outermost atomic layer of surfaces, ideally complements XPS. Both techniques are, for the most part and for many surfaces, non-destructive.

As examples of the combined use of XPS and LEIS, we present the analyses of hydrogen-terminated, single-crystal diamond and various copper samples. First, hydrogen-terminated, single-crystal diamond is a low free energy material that can be easily cleaned. We show the reaction of hydrogen-terminated diamond with atomic oxygen and follow that oxidation by XPS and LEIS. We then reduce this surface with atomic hydrogen, again following this process with XPS and LEIS. The different functional groups that are created by oxidation and then removed by hydrogen reduction are identified and quantified by both techniques. Second, the analysis of copper highlights the extraordinary surface sensitivity of LEIS. Quantities of surface oxygen that minimally affect the XPS spectra (compared to the spectrum of the pure, unoxidized metal), very strongly alter the LEIS spectra. For example, copper metal itself is very inefficient at reionizing helium projectiles, while oxygen at the copper surface is. This difference leads to a dramatic difference in the reionization backgrounds of copper metal and oxidized copper.

For the reasons discussed in this talk, we believe that the combination of XPS and LEIS will play an increasingly important role in surface analysis.

9:00am **CA-FrM-4 Capacitively and Electrically Detected Magnetic Resonance in 4H SiC MOSFET***,* ***Artur Solodovnyk****, P. Lenahan,* The Pennsylvania State University

Silicon carbide MOSFETs show great potential in high-power, high-temperature applications. However, electrically active interface traps, which have a substantial impact on the device's channel-carrier mobility and threshold voltage stability are still not completely understood [1]. Several spectroscopic techniques can help identify the physical and chemical nature of such defects, among them, electrically detected magnetic resonance (EDMR)[2] and as we show in this work, capacitively detected magnetic resonance (CDMR). To the best of our knowledge, CDMR was first demonstrated in Si-based MOS devices by Brandt and coworkers [3-4]. In this work, we show that such capacitive measurements are also possible in SiC-based devices. Furthermore, we compare EDMR and CDMR measurements on the same devices at very different fields and frequencies. The line-widths and g-tensors are approximately the same for both cases. We report on EDMR and CDMR studies on 4H SiC MOSFET in capacitor configuration (gate-body). The relatively narrow line with $g_{\perp}$= 2.0023(±0.0005) and $g_{||}$ = 2.0010(±0.0005) with the respect to the device’s SiC/SiO_2 interface has been observed in both EDMR and CDMR. We observe close similarities at low (500 MHz, Fig. 1) and high frequency (9.784 GHz, Fig. 2) with negative bias of 3 V for both measurements. The line-width at both measured frequencies is about 6.8(±0.3) G. The measurements were carried out at room temperature.

It should be noted, that these measurements were made on devices with quite high interface trap density [5]. Thus, we feel the significance of this work, is mainly to point out the potential utility of CDMR in studies of SiC MOSFETs.

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[1] Chaturvedi, M. et al. Energies 16, 1771 (2023)

[2] C. J. Cochrane et al. Appl. Phys. Lett. 100, 023509 (2012)

[3] M.S. Brandt et al. Appl. Phys. Lett. 76, 1467–1469 (2000)

[4] M.S. Brandt et al. Physica B 273-274, 1027-1030 (1999)

[5] D. J. Meyer et al. Appl. Phys. Lett. 86, 023503 (2005)

9:15am **CA-FrM-5 Photoluminescence Mapping of Gallium Oxide Surfaces and Epilayers***,* ***Matthew McCluskey,*** Washington State University

Photoluminescence (PL) spectroscopy is an important method to characterize dopants and defects in gallium oxide. 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 as short as 266 nm reveals the spatial distribution of these features with submicron resolution. 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. Homoepitaxial layers grown by metalorganic chemical vapor deposition (MOCVD) show defects that are observed via the shifts in the PL band, likely due to the strain field around a dislocation core. Damage due to high-intensity, sub-bandgap laser pulses results in a drop in the intensity of the UV band. A ring or “halo” around the damaged region is observed under 532 nm excitation, attributed to color center defects.

9:30am **CA-FrM-6 Focused Ion Beam Low Energy Implantation** *, M. Titze, C. Smyth,* Sandia National Laboratory*; J. Poplawsky,* Oak Ridge National Laboratory*; B. Doyle, E. Bielejec,* ***Alex Belianinov,*** Sandia National Laboratory **INVITED**

Ion implantation is a key capability for the semiconductor industry. As devices shrink, novel materials enter the manufacturing line, and quantum technologies transition to being more mainstream, traditional implantation methods fall short in terms of energy, ion species, and positional precision. However, lowering the implantation energy while maintaining nanometer scale spot size is a technological challenge. This presentation will show an overview of techniques at Sandia National Laboratories Ion Beam Facility that allow focused ion implants 10-200 keV range for quantum relevant applications.

Additionally new developments in sub-1 keV focused ion implants into Si and 2D devices, using a focused ion beam system, validated by atom probe tomography will be shown. We illustrate that identical results for low energy ion implants can be achieved by either lowering the column voltage, or decelerating ions using bias – while maintaining good spatial resolution. Furthermore, our data reveal that standard implant modeling approaches overestimates experimental depth by a significant margin. Finally, we discuss how our results pave a way to much lower implantation energies, while maintaining high spatial resolution.

10:00am **CA-FrM-8 NIST Nanocalorimetry for In-Plasma Process Metrology Relevant to Semiconductor Fabrication***, **Andrei Kolmakov**, J. Diulus, F. Yi, D. LaVan,* NIST-Gaithersburg

Plasma processing is among the most widely used technologies in semiconductor fabrication industry. In particular, plasma is employed for (reactive-) plasma etching, wafers cleaning, plasma-assisted chemical/physical vapor depositions and etc. However, despite variety of existing plasma diagnostics methods, there is a shortage of metrologies for *in situ* sensitive monitoring/control of the interfacial interactions relevant to semiconductor fabrication. This is particularly valid for plasma processing that relies on neutral reactive radicals and/or pulsed radicals' exposures, which are hard to detect. The current state of the art method for radials detection in research lab settings are based on catalytically activated thermocouples or quartz microbalance based etch sensors which are often too slow or not sensitive enough.

On the other hand, modern microfabricated nanocalorimeters can operate at kHz frequency domain rage and can detect fast physical and chemical (endo-)exothermal surface reactions with high sensitivity on the order of a nJ/K, including adsorption–desorption processes, interfacial reactions, chemical etching reactions all relevant to fabrication of semiconductor devices. Nanocalorimeters are small to be easily integrated to any microfabrication chambers and cheap enough to be readily modified to meet a specific process requirement.

Here we repot the pilot tests of NIST microfabricated nanocalorimeters to detect reactive radicals generated by low power (ca 20-70 W) remote (ca 10 Pa) hydrogen plasma. The setup consists of two otherwise identical sensors but one of them having Au layer exposed to vacuum. Au layer serves as a catalyst with known hydrogen recombination coefficient and the difference in heat of the recombination reactions is detected comparatively by activated and inert nanocalorimeters. The second non-activated sensor is also used to discriminate against parasitic signals such as UV-Vis radiation, ions and electrons fluxes. The setup was successfully tested and major parameters such as sensitivity and response time have been estimated and compared with existing plasma diagnostic tools.

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