CHIPS Act : Semiconductor Manufacturing Science and Technologies
Room 207 A W - Session CPS+MS1-MoM
Metrology for Semiconductor Manufacturing

Moderators: Alain Diebold, University at Albany-SUNY, **Daniel Lu**, CHIPS for America, U.S. Dept of Commerce

8:15am **CPS+MS1-MoM-1 Advancing Semiconductor Manufacturing: The Need for a Metrology Hub in North Texas***, **Moon Kim**,* University of Texas at Dallas **INVITED**

As semiconductor technology advances into new and emerging domains, precise and reliable metrology becomes increasingly critical. However, the escalating cost of advanced semiconductor characterization and metrology equipment, coupled with the specialized expertise required for operation and data interpretation, presents a significant barrier for academic institutions, startups, and even established companies. The absence of a dedicated regional semiconductor metrology center limits access to cutting-edge characterization tools, slowing innovation, increasing costs, and creating bottlenecks in research and development. Establishing such a center would provide shared access to state-of-the-art instrumentation, alleviating the financial burden of acquiring and maintaining expensive tools while fostering collaboration between industry and academia. This would accelerate technological advancements by ensuring high-throughput, high-precision analysis essential for semiconductor materials and device innovation.

Beyond addressing equipment and expertise gaps, a regional metrology center would serve as a critical workforce development hub, training the next generation of engineers and scientists in advanced metrology techniques. The growing semiconductor industry in Texas, particularly in North Texas, underscores the urgency of such an initiative. Texas has been the nation's top exporter of semiconductors and electronic components for 12 consecutive years. Moreover, the region is poised for significant growth, with major investments from Texas Instruments and GlobalWafers exceeding $38 billion and creating over 4,900 jobs. Without a dedicated metrology infrastructure, the region risks falling behind in the global semiconductor race. In this talk, I will discuss the pressing need for a regional semiconductor metrology center in North Texas, its potential impact on industry and academia, and the opportunities it presents for driving innovation and economic growth.

8:45am **CPS+MS1-MoM-3 Template Matching Approach for Automated Determination of Crystal Phase and Orientation of Grains in 4D-STEM Precession Electron Diffraction Data for Hafnium Zirconium Oxide Ferroelectric Thin Films***, **Alain Diebold**,* CNSE, University at Albany, SUNY*; Colin Ophus,* Stanford University*; Amir Kordijazi,* University of Southern Maine*; Steven Consiglio,* TEL Technology Center, America, LLC*; Sarah Lombardo, Dina Triyoso, Kandabara Tapily,* TEL Technology Center, America, LLC, USA*; Ana Mian,* TESCAN GROUP, Inc.*; Nithin BVI Shankar,* TESCAN GROUP, a.s., Czechia*; Tomáš Morávek,* TESCAN GROUP, a.s.,*; Narendraraj Chandran,* TESCAN GROUP, a.s, Czechia*; Robert Stroud,* TESCAN GROUP, Inc.*; Gert Leusink,* TEL Technology Center, America, LLC

Hafnium and zirconium oxide based thin films deposited by atomic layer deposition (ALD) are used as dielectric layers in advanced semiconductor devices. These films can also be stabilized in a ferroelectric phase for applications in memory, logic, and synaptic devices. ALD typically produces small-grained polycrystalline films containing a mixture of ferroelectric and non-ferroelectric phases with varying crystallographic orientations. Routine characterization of these films is critical for the research, development, and manufacturing of next-generation devices. While X-ray diffraction (XRD) is widely used for phase identification, it is limited to large-area, unpatterned thin films. Electron microscopy-based methods, in contrast, enable site-specific characterization within device structures, where local phase distributions may differ from blanket film samples.

This presentation discusses automated analysis of four-dimensional scanning transmission electron microscopy (4D-STEM) precession electron diffraction (PED) datasets for hafnium zirconium oxide (HZO) thin films in TiN/HZO/TiN capacitor structures. STEM lamellae are often thicker than the average HZO grain size, resulting in dynamical diffraction contributions from multiple grains at many probe positions. Additionally, distinguishing between HZO crystal phases is challenging due to small differences in lattice parameters and the potential presence of multiple orthorhombic polymorphs, making automated phase mapping particularly difficult. PED offers advantages over nanobeam electron diffraction (NBED) for phase and orientation analysis, and we find that PED is necessary for reliable automated template matching in HZO diffraction data.

Although automated phase and orientation mapping of HZO films using 4D-STEM has been previously demonstrated, a detailed assessment of different analysis methods has been lacking. Here, we compare results from a commercial software package (NanoMEGAS ASTAR) with an open-source framework (py4DSTEM). Correlation between automated phase maps and electrical verification of ferroelectricity confirms the identification of the non-centrosymmetric orthorhombic space group 29 phase of HZO.

9:00am **CPS+MS1-MoM-4 Multi-Wavelength Atom Probe Tomography***, **Luis Miaja-Avila**, Benjamin Caplins, Jacob Garcia, May Martin,* NIST*; Ty Prosa,* CAMECA Instruments Inc.*; Norman Sanford, Ann Chiaramonti,* NIST

Atom probe tomography (APT) is a sensitive analytical tool capable of providing 3D atomic reconstructions with isotopically resolved elemental and sub-nm spatial resolution. In the field of semiconductor manufacturing, it is used for failure analysis, process development, and competitive engineering. The highly complex, multi-element heterogenous structures of modern electronic devices require APT tools capable of quantitative analysis of samples containing layers with different optical, thermal, and electrical properties. Current state-of-the-art commercial APT instruments use a deep ultraviolet (DUV) light source with a wavelength of 257 nm (4.8 eV photon energy) to trigger the process of field ion evaporation from the samples under study. Historical progression of commercial APT instruments has shown that using shorter wavelength light sources results in improvements in sample survivability, especially for heterogenous samples, which is crucial for the study of semiconductor devices. In support of the semiconductor manufacturing industry, our group proposed and was tasked with the development of an APT instrument that employs a variety of wavelength sources. At NIST we are designing a beamline capable of delivering several different wavelengths (515 nm, 343 nm, 257 nm, and 206 nm) to the APT sample with similar beam parameters. This new multiple wavelength APT instrument will enable a careful study of the benefits and potential drawbacks of each triggering wavelength, with special emphasis on sample survivability, background signal, and mass resolving power. Our mission is to explore the APT wavelength parameter space using different triggering light sources to identify the ideal wavelength, or combination of wavelengths, best suited to improve the study of complex heterogenous semiconductor devices with APT.

9:15am **CPS+MS1-MoM-5 Metrology for Validated Mass Transport Models of Vapor Phase Deposition Processes***, **Berc Kalanyan**, Vladimir Khromchenko, James Maslar,* National Institute of Standards and Technology (NIST)

Digital twins of semiconductor unit processes are being pursued for virtual process development, optimization, and real-time control applications. A digital twin of a vapor phase deposition process may consist of multiple linked models representing reactive transport processes at disparate length scales from the process equipment level to the device structures on the wafer. Development of such models is currently hindered by a lack of non-proprietary process data that could be used for model validation. This talk will introduce efforts at NIST to generate process data and validated models for atomic layer deposition (ALD) processes. An important component of this effort is *in situ* metrology development to access key process parameters such as partial pressures, flow rates, temperature, and mass uptake during deposition at various locations within the process equipment. In this talk we will focus on 1) mass transport measurements within a research-grade ALD reactor and 2) the use of transport data to validate flow simulations. To obtain the process data we use absorption imaging of precursor flow as a function of process conditions, *e.g.*, gas flow rate, chamber pressure, and temperature. Two precursors selected for this investigation are molybdenum pentachloride ($MoCl_5$) and tetrakis(dimethylamido)titanium (TDMAT). $MoCl_5$ flow was visualized at about 100 frames per second in the ultraviolet-visible spectral region using a CMOS camera and a light emitting diode source. TDMAT flow was visualized at about 30 frames per second in the mid-infrared spectral region using an uncooled microbolometer thermal imager and a blackbody source. Simulations of flow in this chamber were performed using a commercial computational fluid dynamics (CFD) package. CFD simulations of low-volatility precursors in a carrier gas are simplified since the precursor is dilute and the gas properties are that of the carrier gas, properties that are well known for typical deposition conditions. Simulations were validated using the time-dependent, pathlength-integrated precursor concentration obtained from the absorption imaging measurements and the time-dependent total pressure measured at selected locations in the deposition system. In this talk, aspects of both the measurements and simulations will be discussed, including the choice of parameters included in the data set.

9:30am **CPS+MS1-MoM-6 Measuring Thermal Conductivity, Interfacial Thermal Conductance, and Chemical Composition at the Nanoscale with AFM Probes***, Devon Jakob, Alexei Azarov, Dhriti Maurya, Junyeob Song, Vladimir Aksyuk,* ***Andrea Centrone,*** National Institute for Science and Technology (NIST)

The next big wave of innovation in microelectronics will likely stems from the successful integration of heterogeneous materials and devices into new 3D constructs, driven by improvements in yields, energy efficiency and costs. Engineering chips for this novel architecture requires precise knowledge of the thermal conductivity and interfacial thermal conductance of thin films and interfaces, but current thermal metrology is inadequate, especially in terms of spatial resolution and throughput. For example, time-domain thermo-reflectance (TDTR), measures thermal conductivity, by reconstructing the sample thermalization as a function of the probe delay time and fitting the sample decay rate to a thermal model. However, TDTR is not well adapted to mapping applications because of low spatial resolution (> 1 µm) and long measurement times (≈120 s/pixel). Furthermore, TDTR typically requires coating the sample with a metallic transducer layer to increase the signal to noise, which is undesirable.

Photothermal induced resonance (PTIR), also known-as AFM-IR, by the combination of atomic force microscopy (AFM) with IR spectroscopy, is an emergent technique that yield IR spectra and maps with nanoscale resolution using the AFM tip to bypass the light diffraction limit. However, while commercially available AFM probes transduce the sample photothermal expansion, they lack the sensitivity and bandwidth required to measure the fast sample thermalization directly.

Here I will introduce, a wide bandwidth (WD) version of PTIR, pioneered at NIST, that enables imaging of thermal conductivity (*η*), interfacial thermal conductance (*G*) and chemical composition at the nano scale, concurrently and with high throughput (20 ms/pixel). This new measurement paradigm leverages custom optomechanical AFM cantilevers with very low detection-noise (≈1 $fm/Hz^{1/2}$) over a wide (>125 MHz) bandwidth. Thanks to these characteristics the entire, time-domain, thermal expansion and contraction of a sample is measured with high spatial (≈10 nm) and temporal (≈ 4 ns) resolutions and at once, rather than as a function of pump-probe delay as in TDTR. Fitting the time-domain thermalization of the sample to a thermal model enable mapping *η* and *G* at the nanoscale.

Compared to TDTR, WB-PTIR is ≈6000x faster and does not require a transducer layer. Such WB-PTIR measurements are particularly well adapted for measuring samples with low to moderate thermal conductivities, like many packaging materials, and excel in measuring interfacial thermal conductance at the nanoscale with high precision (e.g., ΔG = 2-5% for SU-8 on ZnSe).

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