Plasma and Vapor Deposition Processes
Room Town & Country B - Session PP3-ThA

CVD, ALD, and Laser-based Deposition & Microfabrication Technologies

Moderators: Carles Corbella, National Institute of Standards and Technology (NIST)/ University of Maryland, College Park, USA, **Valentina Dinca**, National Institute for Laser, Plasma, and Radiation Physics, Romania, **Frederic Mercier**, CNRS, Grenoble-INP, University Grenoble Alpes, SIMaP laboratory, France, **Takayoshi Tsutsumi**, Center for Low-temperature Plasma Sciences, Nagoya Universit, Japan

1:20pm **PP3-ThA-1 Unveiling the Potential of Transparent Conductive Materials by Atomic/Molecular Layer Deposition: From Process Synthesis to Functionalization***, Abderrahime Sekkat [abderrahime.sekkat@toulouse-inp.fr],* Univ. Toulouse, CNRS, Toulouse INP, LGC, Toulouse, France., France **INVITED**

From powering renewable energy systems to transforming lighting and data storage technologies, solar cells, electroluminescent displays (ELDs), organic light-emitting diodes (OLEDs), sensors, and printed electronics are driving the next wave of technological innovation. Transparent conductive materials (TCMs) play a key role in enabling and improving the performance of these devices by offering unique advantages for human–device interfaces and information processing. Today, transparent conducting indium tin oxide (ITO) remains the most widely used TCM, thanks to its excellent optical transparency (>90%) and low sheet resistance (<30 Ω/sq)1,2. It currently holds about 55% of the transparent conductive electrode (TCE) market in 20243. However, ITO is brittle, which limits its use in flexible devices, and its dependence on indium, a critical and scarce resource, raises sustainability concerns. To address these limitations, several alternative TCMs are being actively explored, covering inorganic, metallic, and organic material families.In this presentation, I will give an overview of our ongoing work on developing alternative TCMs using different vapor-phase deposition (VPD) methods. I will first focus on the growth of oxide films using atmospheric pressure spatial atomic layer deposition (AP-SALD), an innovative alternative to conventional ALD4. Unlike traditional ALD, AP-SALD relies on the spatial separation of precursors within a 3D manifold head rather than sequential gas injection. This approach enables faster deposition over large areas, making it well suited for scalable manufacturing. I will present some recent results on p-type oxides obtained by this method5–7. I will then show how oxide coatings can be used to improve the stability of transparent electrodes based on silver nanowire networks8,9. Finally, I will discuss the development of conjugated conductive polymers using oxidative VPD, with examples of their integration into real devices10. Overall, this work illustrates a comprehensive approach, from process synthesis to device functionalization, aimed at advancing the next generation of transparent conductive materials.References1. Nanomaterials 14, 2013 (2024).2. APL Mater. 9, 021121 (2021).3. https://www.imarcgroup.com/transparent-conductive-films-market. (Accessed: 24th July 2025)4. Adv. Mater. Technol. 2000657, 1–8 (2020).5. Nat. Commun. 2022 131 13, 1–11 (2022).6. Commun. Mater. 2, 78 (2021).7. J. Mater. Chem. A 9, 15968–15974 (2021).8. Adv. Mater. Technol. 8, 2200563 (2022).9. Adv. Mater. Technol. 8, 2301143 (2023).10. ACS Appl. Polym. Mater. 5, 10205–10216 (2023).* Corresponding author e-mail: abderrahime.sekkat@toulouse-inp.fr

2:00pm **PP3-ThA-3 ALD and Aerosol-Assisted CVD for Surface and Interface Control in Perovskite LED Structures***, Francisco Servando Aguirre Tostado [servando.aguirre@cimav.edu.mx],* Centro de Investigacion en Materiales Avanzados, Mexico **INVITED**

Interfacial defects remain a significant impediment to the development of high-performance, stable perovskite light-emitting diodes (PeLEDs). This work presents a comprehensive approach to surface and interface control via complementary chemical vapor deposition methodologies. We employ Atomic Layer Deposition (ALD) to fabricate nanoscale, conformal metal oxide layers such as Al_2O_3, ZnO, SnO_2, and NiO that serve as both efficient charge-transport layers and moisture barriers. The self-limiting nature of ALD ensures perfect coverage on complex nanostructures, mitigating current leakage and shunt paths. On the other hand, we use Aerosol-Assisted Chemical Vapor Deposition (AACVD) to deposit the perovskite emissive layer, where the precursor solution mixture ratio controls the composition and crystalline phase. AACVD overcomes the limitations of spin-coating by enabling the deposition of uniform, pinhole-free films over large areas with precise control of cation stoichiometry, thereby enhancing photoluminescence quantum yield (PLQY) and spectral purity. The talk will detail the optoelectronic and morphological characterization of these interfaces and correlate them with the device performance. Our results, demonstrating PeLEDs with improved external quantum efficiency (EQE) and a lifetime extended by an order of magnitude, underscore the transformative potential of combining ALD and AACVD for large-area and low-cost optoelectronic devices.

2:40pm **PP3-ThA-5 In-Plasma XPS: a New Metrology Tool for Semiconductor Process Development and Control***, Andrei Kolmakov [andrei.kolmakov@nist.gov],* NIST-Gaithersburg, USA **INVITED**

Modern ambient pressure X-ray photoelectron spectroscopy (AP-XPS), in addition to its real-time sub-monolayer sensitivity, now covers the pressure range typical of standard plasma processing applications, naturally expanding the capabilities of AP-XPS for operando plasma-assisted control. We recently demonstrated that XPS spectra can be successfully collected under plasma conditions, extending the application of XPS to plasma-surface-liquid-vapor interactions [1]. In previous work [2], we highlighted the importance of plasma chamber wall reactions on sample surface chemistry and showed that plasma-XPS can capture plasma chemistry both at the surface and in the gas phase. We recently applied plasma-XPS to industry-relevant and realistic poorly conducting surfaces, where we observed anomalous XPS binding energy shifts due to sample charging during an AC plasma exposure. We propose mechanisms that explain these plasma-induced shifts. Additionally, we noted plasma-induced binding energy shifts and peak splitting when measuring XPS from the plasma gas phase. The latter can be used for local diagnostics of the local plasma environment.

Overall, plasma-XPS metrology is a new emerging tool that offers significant potential for advancing real-time diagnostics of plasma-assisted deposition processes, and immediate mitigation strategies to reduce the damage of wafers, which is a well-known challenge in semiconductor fabrication [3].

References

[1] J.T. Diulus, A.E. Naclerio, J.A. Boscoboinik, A.R. Head, E. Strelcov, P.R. Kidambi, A. Kolmakov, The Journal of Physical Chemistry C, 128 (2024) 7591-7600.

[2]] J. T. Diulus, A. R. Head, J. A. Boscoboinik, and A. Kolmakov, J. Vac. Sci. Technol. A 43, 040401, (2025)

[3] K.P. Cheung, Plasma charging damage, Springer-Verlag, London, 2000.

3:20pm **PP3-ThA-7 Plasma Dynamics in Femtosecond Laser Burst-Mode Ablation of Metals for Thin-Film Applications***, Asma Banshamlan [asma.banshamlan@univ-st-etienne.fr], Florent Bourquard, Anne-Sophie Loir, Jean Pierre Chatelon, Christophe Donnet, Florence Garrelie, Bossuet Lilian,* Université Jean Monnet Saint-Étienne, CNRS, Institut d'Optique Graduate School, Laboratoire Hubert Curien, UMR 5516, F-42023 Saint-Etienne, France

The use of femtosecond laser PLD (fs-PLD) has originally been shown to generate controlled distributions of nanoparticles rather than smooth films. The ultrashort pulse duration, shorter than the electron–phonon coupling time, drives rapid, non-equilibrium phase transitions from the metallic to the ionized state, resulting in nanoparticle formation upon cooling.

However, recent advances in femtosecond laser burst-mode operation (coupling MHz and/or GHz bursts), where multiple ultrashort pulses are delivered in rapid succession, enable precise control over the temporal energy deposition compared to single-pulse irradiation. In this study, we investigate burst-mode ablation of metallic targets, including vanadium and tungsten, under varying burst parameters, using ICCD imaging resolved on the nanosecond timescale. These measurements reveal that intra-burst pulse spacing strongly modulates plasma density, particle emission, and expansion dynamics.

Our results show that GHz burst-mode irradiation produces larger plasmas with controlled vapor plume characteristics, substantially reducing nanoparticle formation and facilitating smoother thin-film deposition. These results are confirmed by thin-film characterizations using electron microscopy and atomic force microscopy, demonstrating the ability to obtain smooth surfaces. This work provides fundamental insights into energy coupling and material removal in fs burst-mode ablation and highlights its potential for tailored plasma-assisted fabrication and optimized vapor deposition processes, particularly for including metals in multilayers or even for optimizing Atomic Layer Deposition.

Pulsed-Laser Deposition (PLD) has attracted a lot of interest due to its non-contact nature, its versatility, ease of co-deposition using several targets, and the possibility to perform deposition in ultra-high vacuum conditions, limiting contamination of samples. However, droplet formation has strongly limited its applications for metallic thin-film generation, particularly in the case of multilayer formation including metals.

4:00pm **PP3-ThA-9 Ultrathin SiN_X Membrane Stability Under Energy Fluxes from Non-Thermal Plasma Discharges Monitored via Nanocalorimetry***,*
Carles Corbella [carles.corbellaroca@nist.gov]*,* National Institute of Standards and Technology (NIST)/ University of Maryland, College Park, USA*; Feng Yi, Andrei Kolmakov,* National Institute of Standards and Technology (NIST), USA

Freestanding ultrathin silicon nitride (SiN_x) membranes are widely used as an electron, X-ray, and light transparent windows for environmental spectromicroscopy, separation membranes, and in microelectronics, e.g., as in MEMS devices and nanocalorimeters. However, their stability in the plasma environment requires further studies. Here, suspended 100 nm-thick SiN_x membranes have been wafer-scale fabricated on 15 mm^2-silicon frames using lithography. A platinum lithographically defined resistive microsensor of 100 nm thickness is deposited on the backside of the membrane, and it is calibrated for thermometry and calorimetry. This energy flux sensor (nanocalorimeter) has been exposed to cold plasmas in a custom-made research reactor equipped with a remote inductively coupled plasma (ICP) discharge source, Langmuir probe, retarding field energy analyzer, and optical emission spectroscopy (OES) channel. Energy fluxes (ions, electrons, energetic neutrals, and photons) from plasma plume are registered via sensor temperature evolution upon variations in the plasma parameters. The power carried by plasma species can be estimated from a simple energy balance model in measurements using sensor temperature variations up to a few hundred Kelvin with time resolution below 40 ms [Diulus et al, J. Vac. Sci. Technol. B 43, 020601 (2025)]. Additionally, the measurement setup allows for decoupling of the heating contributions by ions and VUV/UV-Vis-IR photons. It was found that the lifetime of the sensor is defined by the SiN_x sputtering rate combined with thermally induced mechanical stress. Ultrathin SiN_x membranes appear to be very robust even when immersed in the RF plasma plume region, manifesting low sputtering yield under typical electrically grounded experimental conditions. To investigate the chemical stability of the ultrathin membranes, nanocalorimetry experiments in argon plasma have been followed by preliminary tests using reactive gases such as oxygen and hydrogen.

4:20pm **PP3-ThA-10 Conformal PEALD-SiNx Passivation for GaN Vertical SBDs: A Microfabrication Solution to Mesa-Induced Interface Damage***,*
Jiayu Zeng, ***Xuetong Zhou [zhouxuetong@mail.sim.ac.cn]****, Li Zheng, Xinhong Cheng,* State Key Laboratory of Materials for Integrated Circuits, Shanghai Institute of Microsystem and Information Technology, Chinese Academy of Sciences, China

Gallium Nitride (GaN) vertical power devices are pivotal for next-generation high-voltage applications. A critical challenge in their fabrication, particularly for devices utilizing deep mesa etch termination (DEMT) for field management, is the severe surface damage and trench-like defects induced by aggressive etching processes. These defects become dominant leakage paths, severely degrading breakdown voltage and preventing the realization of ideal avalanche breakdown. Conventional dielectric deposition methods like plasma-enhanced chemical vapor deposition (PECVD) struggle to conformally cover these high-aspect-ratio features, leading to interfacial voids and inadequate passivation.

This work presents a microfabrication strategy to overcome this limitation by employing plasma-enhanced atomic layer deposition (PEALD) for conformal silicon nitride (SiN_x) passivation. We demonstrate the growth of high-quality SiN_x films via an optimized PEALD process using a Si_2Cl_6 precursor under ultra-high vacuum. The process, stabilized at 450℃ and 150 W plasma power, yields films with exceptional uniformity (<±1% thickness variation on a 6-inch wafer), low surface roughness (RMS ~0.3 nm), and near-zero oxygen contamination.

The efficacy of this PEALD-SiN_x film was investigated in GaN vertical Schottky barrier diodes (SBDs) with a 6 μm deep mesa. Cross-sectional HRTEM and EDS analysis confirmed that the PEALD-SiN_x provides a conformal, void-free interface, effectively filling etching-induced trenches and mitigating the underlying damaged GaN layer. In stark contrast, PECVD-SiN_x passivation resulted in a defective interface with significant Si diffusion and incomplete coverage. Electrical characterization revealed a transformative improvement in device performance. SBDs passivated with PECVD-SiN_x alone suffered from severe voltage-dependent leakage, reaching 1 mA at just 80 V without breakdown. Conversely, PEALD-passivated devices exhibited a stable, ultra-low leakage current (~10^{-11} A) until a sharp avalanche breakdown at approximately 400 V, a five-fold increase in breakdown voltage and a 10^4-10^5 reduction in leakage. Inter-anode leakage measurements further confirmed that PEALD passivation completely suppressed the sidewall conduction path, restoring bulk-limited conduction.

In conclusion, this study establishes PEALD-SiN_x as an essential micro-fabrication technology for enabling high-voltage GaN vertical devices. Its superior conformality and interface quality directly address the core challenge of etching-induced damage, unlocking the full voltage-blocking potential of DEMT structures and paving the way for robust, high-performance GaN power electronics.

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