ALD Applications
Room Ybor Salons I-IV - Session AA-MoA
Quantum ALD Applications

Moderators: Robert Clark, TEL Technology Center, America, LLC, **Arpita Saha**, Oxford Instruments

4:00pm **AA-MoA-11 Two Level Systems Mitigation by Atomic Layer Deposition for Quantum Application***, **Thomas Proslier**, Yasmine Kalboussi, Théo Dejob, Fabien Eozenou, Gregoire Jullien,* CEA Saclay, France*; sandrine Tusseau-nenez,* Ecole Polytechnique - CNRS, France*; Nathalie Brun, Michael Walls,* Université Paris-Saclay, France*; frédéric miserque, Maurice Luc,* CEA Saclay, France **INVITED**

Superconducting quantum bits (qubits) are regarded as one of the key technological building blocks for future quantum computers and sensors. One of the primary obstacles to extending qubit performance and in particular their coherence times is the presence of photon-absorbing defects, commonly modeled as two-level systems (TLS). Microscopic sources of TLS—such as oxygen vacancies, hydroxyl groups, and amorphized structures—have been identified in dielectric surfaces, interfaces, and Josephson junctions. Thanks to its atomic-scale control of composition and thickness, atomic layer deposition (ALD) offers a powerful approach to address this challenge and mitigate some of these defects mechanisms. ALD is also fully compatible with standard microelectronic fabrication processes and can be readily integrated into the production of two-dimensional superconducting films.

Niobium (Nb) superconducting cavities, widely used in particle accelerators, provide a simpler type of resonator compared to qubits, with the advantage of involving only a single interface—Nb and vacuum. This makes them ideal platforms for investigating how the structure, chemical composition, and thickness of various oxide capping layers affect resonator performance and TLS properties.

I will present performance measurements from Nb superconducting resonators coated via ALD with amorphous as well as crystalline films with thicknesses between 2 and 10 nm. Following thermal treatments, these coatings were found to enhance quality factors and coherence times relative to bare niobium with its native oxide. TLS-model fits of RF measurements, combined with surface characterization techniques such as XPS and TEM, enable the extraction of TLS properties—including dielectric losses and defect concentrations—in the various capping layers.

These findings offer valuable insight for future technological developments of superconducting resonators operating in the quantum regime, including qubit architectures.

4:30pm **AA-MoA-13 Atomic Layer Deposition Based Dopant Engineering of Er-Doped CeO_2 Thin Films for Scalable Quantum Materials***, **Terrick McNealy-James**,* University of Central Florida*; Emily Miura-Stempel, Ratul Mangalr,* University of Washington*; Justin Moore, Diego Javier-Jimenez, Titel Jurca,* University of Central Florida*; Brandi Cossairt,* University of Washington*; Parag Banerjee,* University of Central Florida

Quantum information technology has the potential to transform sensing, communication, and computing by exploiting intrinsic spin-photon interfaces of rare-earth-ions (REIs). These spin-photon interfaces stem from the shielded 4f-shell electrons of REI's, which give rise to long-lived electron spin states and long coherence times. When combined with the compatibility of solid-state dielectric host materials with established silicon-based integration and fabrication technologies, REI's can become a promising pathway towards developing scalable solid-state quantum platforms.

Among the candidates for host materials, cerium oxide (CeO_2) is an attractive option with its crystalline morphology, wide band gap (3.19 eV) and low concentration of nuclear spins, all of which contribute to reduced magnetic noise and a theoretically predicted coherence times of up to 47 ms. Building on these characteristics, erbium-doped cerium oxide (Er:CeO_2) has become a compelling solid-state material for spin-based quantum information processing. Studies of Er:CeO_2 nanoparticles have demonstrated long electron spin coherence times in the microsecond range. However, the morphology and particulate nature of nanoparticles present a significant challenge for large scale integration into solid-state device architectures.

In this work, we address these challenges by developing Er:CeO_2 thin films via atomic layer deposition (ALD), a gas phase, wafer scale technique capable of angstrom-level thickness control, conformal coating, and precise dopant incorporation. Two distinct ALD based doping strategies are investigated and compared. The first approach uses a super cycle method, in which Er_2O_3 cycles are periodically inserted into CeO_2 growth sequence to control dopant concentration through cycle ratio adaptations. The second, less-explored approach utilizes co-dosing of erbium and cerium precursors in the same ALD cycle with the goal of achieving a more spatially dispersed dopant distribution.

To establish an understanding of each doping strategy dual and tandem techniques of *in situ* quadrupole mass spectrometry (QMS) and spectroscopic ellipsometry (SE) are used to monitor film growth behavior and gas-phase reaction chemistry during deposition. *Ex situ* techniques including x-ray photoelectron spectroscopy (XPS), x-ray diffraction (XRD), and Raman spectroscopy are used to correlate dopant incorporation pathways with structure-property relationships. Additionally, pump-probe spectroscopic techniques will measure the lifetimes of the spin polarized electrons in Er:CeO_2 and benchmark their performance to state-of-art, spin-photon systems.

4:45pm **AA-MoA-14 Superconducting Nitrides by Fast Remote Plasma ALD for Quantum Applications***, **Harm Knoops**, Arpita Saha, Dmytro Besprozvannyy, Nick Chittock,* Oxford Instruments Plasma Technology, UK*; Silke Peeters, W.M.M. (Erwin) Kessels,* Eindhoven University of Technology, Netherlands*; Ciaran Lennon,* Oxford Instruments Plasma Technology, UK*; Nidhi Choudhary, Robert Hadfield,* University of Glasgow, UK*; Iliya Shiravand, Davood Shahrjerdi,* New York University*; Christos Zachariadis, Alessandro Bruno,* QuantWare B.V., Netherlands

Superconducting films ranging from a few to hundreds of nanometers are at the basis of a wide range of quantum devices and are therefore key in advancing quantum technology to an era of widespread utility. The further development of quantum technologies hinges on improvements in materials and their interfaces using scalable processing. With its atomic-scale growth control and wafer-scale uniformity, plasma-enhanced ALD (PEALD) could become an enabling technique for the growth of superconducting thin films with high-quality interfaces. High-throughput processes would facilitate the growth of films beyond the few tens of nanometers, broadening the application perspective for ALD of superconducting films.

We demonstrate PEALD including substrate biasing for a variety of superconducting nitride films ranging from 5 to 100 nm thickness, with a high throughput of up to > 50 nm/houron the PlasmaPro ASP system. The nitrides TiN, NbN, NbTiN, and TaCN are deposited and investigated through a range of collaborations with the intent to show their utility for quantum device applications.

Extensive material analysis shows how NbN, TiN, and NbTiN have useful film properties and remain superconducting down to low thicknesses.[1,2] Substrate biasing during PEALD enables tuning of the materials properties either by reducing contaminants in the film and improving crystallinity to achieve low resistivities, or by increasing disorder for applications such as microwave kinetic inductance detectors. For Nb and Ta compounds the presence of carbon is interesting in that it can be present in the form of superconducting carbonitrides (shown for Nb and Ta compounds).[2,3] Furthermore, these carbonitride films were found to support high internal quality factors exceeding 10^5 at 50 mK in the single-photon regime.[3]

The wide parameter space enabled by PEALD was also found to allow for high-quality planar TiN films. As an example, two samples achieved a T_c of 4.583 ± 0.005 K and 4.700 ± 0.005 K respectively with a narrow transition width of 0.007 ± 0.003 K indicating high material quality with minimal contamination. Further collaboration with partners is ongoing to showcase the utility of these films in 3D structures as through-silicon vias. Here several mA of critical current was found per via in preliminary work. These and other results indicate the promise of superconducting nitrides by fast remote plasma ALD for quantum applications.

1. Peeters et al., *AVS Quantum Sci.* **7**, 026801 (2025)

2. Choudhary et al., *APL Mater.* **13**, 111104 (2025)

3. Shiravand et al., *Appl. Phys. Lett.* **127**, 192603 (2025)

5:00pm **AA-MoA-15 Wafer-Scale Thermal ALD of Superconducting TiN: A Scalable Process with Room-Temperature Predictive Mapping***, **Sanaz Zarabi**, John Rönn, Otto Laitinen,* Beneq Oy, Finland

Superconducting thin films are at the heart of next-generation technologies, from quantum computing to ultra-sensitive detectors, but their integration into scalable microfabrication remains a bottleneck. Titanium nitride (TiN), with its tunable superconducting properties and compatibility with CMOS processes, stands out as a key material candidate (1-2). In this work, we report a fully thermal ALD process for TiN deposition on 200 mm wafers using $TiCl_4$ and NH_3 at **480 °C** with **TFS200** reactor, achieving homogeneous films with a superconducting critical temperature (Tc) of **3.65 K** with an average thickness of **45.23 nm,** shown in Figure 1. Importantly, the process is directly scalable to a batch process without degradation in superconducting performance, maintaining a thickness non-uniformity (σ/avg) of **4.34 %**.

To tackle the longstanding limitation of cryogenic, localized T_c measurements, we introduce a non-destructive room-temperature metrology strategy for the first time that correlates **refractive index and extinction coefficient** (measured via **spectroscopic ellipsometry**) with superconducting behavior. This enables rapid, full-wafer assessment of superconductivity without using cryogenic equipment, providing a powerful tool for both process monitoring and device screening. Using this method, we quantify superconductivity non-uniformity (σ/avg) across a 200 mm wafer with 5 mm edge exclusion to be **1.87%** for single-wafer deposition and **1.21%** in batch processing, validating the approach as a powerful tool for scaling superconducting materials into manufacturable device platforms.

Furthermore, we present comprehensive structural and compositional characterization using **TEM**, **XRD**, and **ToF-ERDA** to probe grain structure, crystallinity, stoichiometry, and impurity content. These insights directly link film quality to superconducting behavior, deepening our understanding of how to optimize ALD-grown TiN for quantum and cryogenic applications.

Together, these results establish a scalable, high-performance route to superconducting TiN, backed by both advanced characterization and a practical, predictive metrology framework tailored for real-world manufacturing.

References:

1. Deyu, Getnet Kacha, Marc Wenskat, Isabel González Díaz-Palacio, Robert H. Blick, Robert Zierold, and Wolfgang Hillert. "Recent advances in atomic layer deposition of superconducting thin films: a review." *Materials Horizons* (2025).
2. Grigoras, Kestutis, N. Yurttagül, J-P. Kaikkonen, Elsa T. Mannila, Patrik Eskelinen, D. P. Lozano, H-X. Li et al. "Qubit-compatible substrates with superconducting through-silicon vias." *IEEE Transactions on Quantum Engineering* 3 (2022).

5:15pm **AA-MoA-16 ALD Outstanding Presentation Award Finalist: Growth of Superconducting Trilayer NbN/AlN/NbN Structures for Photonics and Quantum Computing Applications***, **Ciaran Lennon,*** Oxford Instruments Plasma Technology, UK*; Nidhi Choudhary,* University of Glasgow, UK*; Dmytro Besprozvanny,* Oxford Instruments Plasma Technology, UK*; Valentino Seferai,* University of Glasgow, UK*; Arpita Saha,* Oxford Instruments Plasma Technology, UK*; Harm Knoops,* Oxford Instruments Plasma Technology, Netherlands*; Harriet van der Vliet,* Oxford Instruments Plasma Technology, UK*; Robert Hadfield, Martin Weides,* University of Glasgow, UK

Superconducting materials are the building blocks for many nascent quantum technologies that underpin the quantum revolution of the 21st century. Reliable and reproducible growth of superconducting materials, particularly thin films, is paramount for the ongoing progress of the field [1,2]. Plasma-enhanced atomic layer deposition (PEALD) has recently been demonstrated as a promising candidate for superconducting thin film growth, offering superior uniformity, conformality and thickness control to conventional physical vapor deposition techniques, such as sputtering, while exhibiting superior film quality (T_c and J_c) and more compositional variety than thermal ALD [3]. Critically, the role of RF substrate biasing in PEALD of superconducting thin films, allowing for greater ion energy control, has also been shown to improve the superconducting properties and provide more tunability for specific device applications [4,5].

Owing to the sub-nm thickness control and compositional diversity of PEALD, allowing for growth of relatively complex heterostructures, we have identified it as the ideal technique for the growth of superconducting multilayer structures for both superconducting nanowire single-photon detectors (SNSPDs) and Josephson junctions (JJs) [6]. Our work presents a study of the growth of NbN/AlN/NbN trilayer structures using PEALD with RF substrate biasing, with 5 nm NbN layers (SNSPDs) and 30 nm NbN layers (JJs), detailing their structure, morphology, composition and superconducting properties. We report $T_c > 6$ K for 5 nm NbN layers and $T_c >$ 12 K for 30 nm layers. We then present the fabrication of both multilayer SNSPD and JJ structures using electron beam lithography and reactive ion etching. For the multilayer SNSPDs, we present device characterization from 1.5 μm up to 4 μm wavelengths, examining the device performance in the mid-IR. For the JJ structures we present preliminary results detailing the electrical properties, including the critical current density (J_c), of devices tested at millikelvin temperatures.

Overall, this work presents significant progress in the development of a PEALD toolbox for the growth of high-quality superconducting multilayer structures for the development of a variety of superconducting quantum device modalities.

[1] Morozov D. V., et al., Contemp Phys **62** 69–91

[2]de Leon N. P., et al., Science **372** 253

[3]Peeters S. A., et al., Appl Phys Lett **123** 132603

[4]Lennon C. T., et al., Materials for Quantum Technology **3** 045401

[5] Wang D., et al., Nature Materials https://doi.org/10.1038/s41563-025-02448-

[6]Alam S., et al., Coatings **13** 278

Author Index

Bold page numbers indicate presenter