Quantum Science and Technology Mini-Symposium
Room B110-112 - Session QS+EM+TF-MoM

Materials for Quantum Computation and Quantum Information

Moderators: Robert Grubbs, IMEC Belgium, **Dave Pappas**, Rigetti Computing

8:20am **QS+EM+TF-MoM-1 High Stability Metal-Based Single Electron Transistors for Silicon Quantum Dot Charge Sensors*, Runze Li,*** University of Maryland College Park*; P. Namboodiri,* NIST-Gaithersburg*; Y. Hong, N. Ebadollahi,* University of Maryland College Park*; J. Pomeroy,* NIST-Gaithersburg

Extremely stable metal-based single electron transistors (SETs) are fabricated using a plasma oxidation technique, resolving the time stability problem that has been a major disadvantage for metal-based SETs. Metal-based SETs were studied extensively ~20 years ago, but were abandoned due to the much worse instability in the charge sensing results compared to Si-based SETs. The most severe instability was a low-frequency noise called “charge offset drift,” which causes random and unreproducible readout. Our goal is to produce high stability aluminum-based SETs using plasma oxidation and couple them to Si-based QDs as the charge sensor. The plasma oxidation reduces the two-level defects in the tunnel junction, and we consequently gain a significantly lower charge offset drift of $\Delta Q_0 = 0.13$ e ± 0.01 e in 7 days compared to $\Delta Q_0 > 1$ e in 1 day for thermally oxidized Al-SETs in the literature. However, we are only able to get an output current of ~4 pA during our measurements, which is insufficient as a charge sensor. Our current goal is to increase the output current to ~100 pA (similar to the level of Si-based SETs) by lowering the resistance of the AlOx tunnel junctions. Increasing the tunnel junction area will decrease the resistance, but also increase capacitance, so we are reducing the oxidation time from 7 seconds (which is the oxidation duration for the stabilized SETs being made) to 3 seconds, to reduce the resistance of the tunnel junction by ~10 times.

8:40am **QS+EM+TF-MoM-2 High-quality and High Deposition Rate Atomic Layer Deposition of NbN and TiN for Superconducting Quantum Applications***, H. Knoops,* Oxford Instruments Plasma Technology, Netherlands*; L. Bailey, D. Besprozvannyy, M. Powell,* Oxford Instruments Plasma Technology, UK*; **Russ Renzas,*** Oxford Instruments Plasma Technology

Due to the potential of excellent film control, uniformity, and conformality, atomic layer deposition (ALD) is seen as very promising for quantum devices where interface and material quality and their uniformities are a big challenge. Furthermore, for superconducting circuits, the deposition rate of ALD can be an issue, since a high enough film thickness (> 50 nm) is needed to minimize kinetic inductance effects on resonator frequency and where the shielding effectiveness of superconducting vias for crosstalk mitigation depends on film thickness and film conformality in the 3D structures. The challenge here is to deliver sufficiently fast processes while maintaining the desired film properties.

Here, we will share our recent development of a high-quality superconducting NbN and TiN for quantum applications, such as resonators and interconnects, capable of depositing > 50 nm film thickness in two hours. The RF-driven remote plasma source design and chamber of our system is optimized for ALD and allows for deposition rates which are > 3x faster than conventional substrate-biased plasma ALD deposition of similar materials.

The quality of the deposited films was demonstrated to be excellent, as measured by four-point probe electrical resistivity, conformality (100% on 8:1 trench for NbN, verified by SEM), and superconducting transition temperature (T_c). Good superconductive properties of the film were demonstrated by SQUID measurements. Thickness uniformity of < ±5% across a 150 mm Si wafer was achieved with good repeatability. We will also show how stress can be tuned as a function of process parameters, such as the RF source power.

Emerging quantum technologies based on superconducting nitride materials are showing great promise and will benefit not only from the uniformity of the deposition, conformality and film quality, but also from the speed and control provided by this ALD process.

9:00am **QS+EM+TF-MoM-3 Navigating MBE Growth of Atomically Precise Complex Oxides using Source Chemistry*, Bharat Jalan,*** University of Minnesota, USA **INVITED**

From its beginnings as a successful method for III–V semiconductor growth to today for the growth of many contenders for next-generation electronics, spintronics and quantum devices, molecular beam epitaxy (MBE) has been very successful. However, several challenges exist for metal oxide growth where a metal is hard-to-oxidize and/or difficult to evaporate/sublimate. In this talk, I will review these issues and will present my group’s effort to address these challenges using a novel solid-source metal-organic MBE approach. We show, for the first time, controlled synthesis of metal and metal oxides of these “stubborn” elements with the ***same ease and control*** as afforded by III-V MBE. We will present detailed growth study utilizing chemistry of source materials as a controlling knob to navigate synthesis. With the goal to understand and control electronic ground states in defect-managed complex oxide films and nano-membranes, we will discuss how chemistry of source materials can be used to navigate synthesis on-demand.

9:40am **QS+EM+TF-MoM-5 Atomic Layer Deposition of Superconducting Titanium Nitride for Through-Silicon-Via Structures and Photon Detection*, John Femi-Oyetoro,*** *H. LeDuc, P. Day, M. Dickie, F. Greer,* Jet Propulsion Laboratory (NASA/JPL)

Superconducting detectors (SDs) play a crucial role in solving various problems in astronomy and cosmology, including dark matter, exoplanet transit spectroscopy, quantum computing and information. An example of such devices is the microwave kinetic inductance devices (MKIDs). This device has been employed in answering questions about the first light emitted after the big bang approximately 14 billion years ago. SDs make use of thin films of superconducting materials, such as titanium nitride (TiN), because of their high intrinsic kinetic inductance (KI) and large London penetration depth, which makes them particularly interesting and useful. In this study, we demonstrate the atomic layer deposition (ALD) of high-quality TiN with high transition temperature (T_c) and KI suitable for large photon detector arrays and high-density through-silicon-via (TSV) structures. ALD-TiN provides an alternative and reliable source of high-quality films for scarce high-quality sputtering targets. Additionally, these films are expected to be more uniform than reactive sputtered films, which is crucial for cm-scale detector arrays, increasing the absolute detector yield on each wafer. We explored various precursors, gas chemistries, techniques, and deposition conditions, including temperatures as low as 200°C. In particular, we also employed ion bombardmentvia RF biasing for our deposition process. This is a unique method for removing oxygen impurities, a major contributor to low-quality and high-resistivity films. Furthermore, this energy supply facilitates film densification, efficient elimination of precursor ligand residues, and surface adatom diffusion. We are able to repeatedly deposit a film of ~ 54 nm on a planar 6-inch wafer that transitions and superconducts at $T_c = \sim 4.35$ K. Overall, our goal is to produce SC films with spatial uniformity, highly conformal, and high T_c to overcome the challenges of large detector arrays and interconnect density using 3D integration. The results aiding these efforts will be discussed further.

10:40am **QS+EM+TF-MoM-8 Molecular Beam Epitaxy of Superconducting ZrN Thin Films on GaN Substrates*, Brelon May,*** *K. Vallejo, D. Hurley, K. Gofryk,* Idaho National Laboratory

Group III-Nitride materials have found applications in optoelectronics and photonic devices due to the large variation in direct bandgap spanning from the infrared to the deep ultraviolet. Recent research has pursued the integration of this well-established material system with transition-metal nitrides to create complex heterostructures with additional magnetic or superconducting functionality. ZrN is a well-known refractory conductor with high oxidation resistance, high hardness, and has been shown to be a superconductor at low temperatures. The estimated lattice mismatch of ZrN with InN, GaN, and AlN is 8.5%, -1.5%, and -4.2%, respectively, suggesting strain free as well as strain-tunable growth on the ternary III-Ns. This work focuses on the epitaxial growth of ZrN on c-plane GaN substrates via molecular beam epitaxy. An electron beam evaporation source and an RF-plasma source were used to supply the Zr and active nitrogen, respectively. Reflection high energy electron diffraction (RHEED) and X-ray diffraction (XRD) did not reveal any crystallographic texture of ZrN deposited on fused silica at temperatures >700°C. However, growth of ZrN on c-plane GaN substrates at similar temperatures was epitaxial. RHEED revealed that the ZrN maintains the symmetry of the underlying GaN throughout the entire deposition, and post-growth examination via XRD showed (111) oriented ZrN thin films. RHEED patterns during the regrowth of GaN directly on thicker layers of higher symmetry ZrN suggest a preference for twin formation and a slight degree of surface faceting. A physical property measurement system was used to measure electrical transport as a function of temperature and magnetic field. Initial results of uncapped ZrN thin films reveal a superconducting phase with a critical temperature of <10 K and a critical field of 2 T. Because the critical temperature is lower than expected, the presence of off stoichiometry or structural disorder is suspected. These results pave the way for integration of superconductors and quantum phenomena in existing III-N photonic systems.

11:00am **QS+EM+TF-MoM-9 Enhancing Quantum Circuits Through Biased Plasma-Enhanced ALD of Ultrathin Superconducting TaC_xN_{1-x}**, ***Silke Peeters,*** Eindhoven University of Technology, Netherlands*; C. Lennon, V. Seferai, R. Hadfield, M. Weides,* University of Glasgow, UK*; M. Verheijen, E. Kessels,* Eindhoven University of Technology, Netherlands*; H. Knoops,* Eindhoven University of Technology, Oxford Instruments, Netherlands

Superconducting quantum circuits are one of the leading architectures in quantum computing platforms. Recent experiments [1,2] demonstrating up to 0.5 ms coherence time in superconducting Ta transmon qubits mark a six order of magnitude improvement in superconducting qubit coherence over the past two decades [3,4]. However, major material challenges, such as uncontrolled oxides and disordered interfaces, still stand in the way of realizing large-scale, fault-tolerant quantum computers.

In this contribution, material properties of ultrathin TaC_xN_{1-x} are extensively characterized and coupled to cryogenic superconducting quantum device performance. In this way, we aim to clarify the roles of various processing aspects in achieving high-quality-factor devices. TaC_xN_{1-x} films with thicknesses of 7 – 40 nm were prepared by plasma-enhanced atomic layer deposition (PEALD) with radiofrequency substrate bias. Because of its atomic-scale growth control PEALD is a promising technique for growth of thin films with high-quality interfaces. Ion energy control in the ~25 – 250 eV range is provided by the substrate bias.

We have observed that energetic ions can counteract oxygen impurity incorporation and promote a larger grain size, while minimizing ion-induced material damage. Increasing the ion energy from ~25 eV to ~150 eV yields a hundredfold decrease in room-temperature resistivity to 239 μΩ cm for an 18 nm film. Smooth, dense, polycrystalline TaC_xN_{1-x} films of the fcc crystal structure are obtained, which are stable in ambient atmosphere.These films maintain a high critical temperature of superconductivity (T_c) of 7 K down to 11 nm film thickness.

The high ultrathin-film quality achieved by PEALD with substrate bias is promising for ultrathin, low-loss superconducting quantum devices. Specifically, superconducting resonators were fabricated from 20 - 35 nm TaC_xN_{1-x} films on high-quality silicon and sapphire substrates, with preliminary measurements showing internal quality factors of at least $2x10^5$ in the single-photon regime. Furthermore, we provide practical pointers for quantum device compatibility of ultrathin superconducting films. Through the high level of control in PEALD with substrate bias, this work contributes to the understanding of material loss mechanisms in superconducting quantum circuits.

References

1. P. M. Place *et al.* Nat. Commun.**12**, 1779 (2021).
2. C. Wang *et al.* npj Quantum Inf. **8**, 3 (2022).
3. W. D. Oliver and P. B. Welander *MRS Bulletin***38**, 816 (2013).
4. D. Gill and W. M. J. Green *IEEE ISSCC* 30 (2020).

11:20am **QS+EM+TF-MoM-10 Characterization of Ultra-Thin Superconducting TaN Nanowires with Integrated Heatsink Capabilities for SNSPD Applications**, ***Ekta Bhatia,*** NY CREATES*; T. Nanayakkara, C. Zhou,* Center for Functional Nanomaterials, Brookhaven National Laboratory*; T. Vo,* American Institute for Manufacturing Integrated Photonics*; W. Collison, S. Schujman, A. Biedron, J. Nalaskowski, S. Olson,* NY CREATES*; S. Kar,* American Institute for Manufacturing Integrated Photonics*; H. Frost,* College of Nanoscale Sci. & Eng., SUNY Polytechnic Institute*; J. Mucci, B. Martinick, I. Wells, T. Murray, C. Johnson, V. Kaushik,* NY CREATES*; C. Black, M. Liu,* Center for Functional Nanomaterials, Brookhaven National Laboratory*; S. Papa Rao,* NY CREATES

Tantalum nitride (TaN) has emerged as a promising candidate for superconducting nanowire single-photon detectors (SNSPD) due to its favorable properties such as lower T_c that enables easier Cooper-pair breaking and a longer wavelength cut-off [1]. TaN is also attractive because it is widely used in the CMOS IC industry enabling TaN SNSPDs to be readily made at a large scale, on 300 mm wafers. While the body of knowledge about superconducting TaN has been growing, its knowledge at 300 mm scale is limited. In this work, we report on the superconducting properties of 300 mm scale TaN and its dependence on process variables. We then discuss the impact of novel integration schemes on the thermal characteristics of TaN nanowires for SNSPD applications.

Copper encapsulated damascene TaN nanowires (with a N/Ta ratio of 0.53 set by room temperature reactive sputtering conditions) have a coherence length of ~8 nm. This is in rough agreement with prior literature on TaN thin films deposited at 750℃ on sapphire substrates [2]. Extracted values of effective penetration depth, critical magnetic field, and critical current density are reported. We also studied the T_c, I_c dependence on varying thicknesses and line widths (100 nm to 3000 nm). Our TaN nanowires exhibit a T_c of ~3.45 K (at a thickness of ~35 nm) with <5% variation across the 300 mm wafer. Sheet resistance (at 300 K) and I_c vary by < 5% across the 300 mm wafer for all the line widths measured, similar to the < 5% across-wafer non-uniformity of thickness (XRR) and N/Ta ratio (SIMS & XPS). We also investigated the superconducting properties of different in-film N/Ta ratios varying from 0.35 to 0.7 using 20 nm thick nanowires.

We explored the efficacy of Cu as a heat transport material that is integrated with TaN nanowires in various schemes (damascene Cu above the nanowire, and a blanket underlayer of Cu) and compared to a control case with no Cu. We used the ratio of retrapping current to I_c as the metric of heat transfer efficiency. This study demonstrates a novel way to increase heat transport away from the nanowire, hence improving the reset times of SNSPDs. We discuss one possible design of a focal plane array of fast SNSPDs based on the findings of this work. This study further strengthens the case for scalable fabrication of TaN nanowires using state-of-the-art 300 mm process tools, with applications ranging from arrayed detectors for cosmology to single photon detection in photonic quantum computing and superconducting optoelectronic neuromorphic computing.

[1] A. Engel *et al.* Appl. Phys. Lett. **100**, 062601 (2012).

[2] K. Il'in *et al.* Physica C **470**, 953–956 (2010).

Authors 1 and 2 contributed equally.

11:40am **QS+EM+TF-MoM-11 Cryogenic Microwave Loss Measurements of Metal-Oxides using 3D Superconducting Cavities**, ***Nicholas Materise,*** Colorado School of Mines, USA*; J. Pitten,* University of Colorado Boulder*; W. Strickland, J. Shabani,* New York University*; C. McRae,* University of Colorado Boulder/National Institute for Science and Technology (NIST)

Reports of high performance tantalum-based qubits has stimulated interest in comparing the quality of tantalum pentoxide with niobium pentoxide and suboxides of niobium. Here, we present a high participation cavity capable of resolving differences in losses due to oxides grown on Ta and Nb thin films. We distinguish losses of the oxide from the other interfaces using in a multi-step measurement process, first measuring the substrate with its native oxide, then repeating the measurement with the film deposited on the same substrate with oxide grown on the surface. Participation ratio calculations estimate the losses due to each interface, with their thicknesses measured by cross-sectional transmission electron microscopy. This measurement capability opens possibilities to screen candidate materials, and their oxides, for use in superconducting qubits and devices.

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