Quantum Science and Technology Mini-Symposium
Room 123 - Session QS-TuM

Superconducting Qubits and Surface Engineering for Quantum Applications

Moderators: David Pappas, Rigetti Computing, **Sisira Kanhirathingal**, Rigetti Computing

8:00am **QS-TuM-1 Cryogenic Growth of Tantalum on Silicon and the Effect of Substrate Preparation on Superconducting Circuit Performance**, ***Teun van Schijndel***, University of California Santa Barbara; *A. McFadden,* NIST-Boulder; *W. Yánez-Parreño, J. Dong,* University of California Santa Barbara; *R. Simmonds,* NIST-Boulder; *C. Palmstrøm,* University of California Santa Barbara

Recent advances in superconducting quantum information systems show the effectiveness of tantalum as a superconducting material, with qubits reaching coherence times up to 0.5 ms[1,2]. The growth of alpha-Ta is required for the realization of desirable superconducting properties. However, challenges persist as various sources of energy losses arise from material-related factors. One of the potential sources comes from the substrate-superconductor interface. Here, we demonstrate cryogenic growth (< 20 K) of polycrystalline alpha-Ta on silicon substrates. First, we show the ability to grow alpha-Ta on different substrate orientations and confirm with X-ray diffraction and transport that we form a similar polycrystalline-oriented film regardless of the substrate orientation. Furthermore, we explore different substrate preparation techniques such as HF etching and *in-situ* Atomic Hydrogen Annealing. We will study the silicon substrates before growth by *in-situ* Scanning Tunneling Microscopy (STM). Next, we perform microwave measurements on fabricated CPW resonator circuits and 2D Transmon qubits and compare the performance of different surface orientations and substrate preparation techniques. We aim to correlate the findings in the microwave measurements with our observations in STM.

1) Place, A.P.M., *et al.*, *Nat Commun* **12**, 1779 (2021).

2) Wang, C., *et al.*, *npj Quantum Inf* **8**, 3 (2022).

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8:15am **QS-TuM-2 Thin Film Growth of Alpha- and Beta-Ta on Low-Loss Oxides for Superconducting Resonator Development**, *N. Price, C. Wade, L. Don Manuwelge Don,* Miami University; *S. Padhye, H. Yusuf, E. Mikheev,* University of Cincinnati; ***Joseph Perry Corbett***, Miami University

Superconducting qubits are one of the leading candidates for creating quantum computers with the potential to surpass modern supercomputers in solving specific problems. Steady progress over the last 20 years has occurred, increasing the lifetime of quantum states and the number of qubits. A popular method to create a 2-level quantum system for quantum computation is to pattern a low-loss insulator/superconductor heterostructure into circuits. A recent new discovery in the qubit community is the fabrication of qubits from α-Ta thin films with improved coherence times of 0.5 ms! Despite recent success, an impetus for fundamental material science on insulator/superconductor heterostructure is well-recognized in the QISE community. We perform a systematic investigation of the nucleation and thin film microstructure of alpha- and beta-Ta grown on several low-dissipation insulating oxide substrates alongside identifying essential growth conditions that result in material conditions that adversely affect the sharpness of superconducting transition and Q-factor. Utilizing a combination of coil-assisted sputtering epitaxy, electron and scanning probe microscopy, alongside millikelvin microwave transport measurements, we uncovered the nucleation and thin film microstructure of alpha, beta, and mixed Ta films. We correlated this with impacts on transition temperature and Q-factor.

8:30am **QS-TuM-3 Quantum Engineering of Superconducting Qubits**, ***William D. Oliver***, MIT **INVITED**

Superconducting qubits are coherent artificial atoms assembled from electrical circuit elements and microwave optical components. Their lithographic scalability, compatibility with microwave control, and operability at nanosecond time scales all converge to make the superconducting qubit a highly attractive candidate for the constituent logical elements of a quantum information processor.Over the past decade, spectacular improvements in the manufacturing and control of these devices have moved the superconducting qubit modality from the realm of scientific curiosity to the threshold of technical reality. In this talk, we present recent progress, challenges, and opportunities ahead in the engineering of larger scale processors based on superconducting qubits.

9:15am **QS-TuM-6 Characterization of Hydroxyls in Surface Oxides of Tantalum and Their Mitigation for Superconducting Qubits**, ***Ekta Bhatia***, *N. Pieniazek, A. Biedron, S. Schujman,* NY CREATES; *H. Frost,* Tokyo Electron Ltd. Technology Center America (TTCA) LLC; *Z. Xiao, S. Olson, J. Nalaskowski, K. Musick, T. Murray, C. Johnson, S. Papa Rao,* NY CREATES

Recently, Ta has attracted more attention [1] in the superconducting quantum community due to the high coherence times in superconducting qubits when it replaces Nb in the capacitor pads [2]. The surface oxides of superconducting metals have been demonstrated to be a major contributor to microwave loss mechanisms [3], and hence to decoherence in superconducting qubits. In this study, we quantify the concentration of hydroxyls [OH], and their variation with depth in various surface oxides of Ta. We also demonstrate, for the first time, that it is possible to modulate the extent to which such tantalum hydroxyls are present by replacing the native oxide of Ta with a chemically-formed surface oxide. Using Time-of-Flight Secondary Ion Mass Spectrometry (ToF-SIMS) analysis, we were able to quantitatively determine the concentrations of TaOH as a function of depth, for both the native oxide of Ta, as well as for the surface oxide that is formed during chemical mechanical planarization of Ta. The effect of fiber texture in the deposited Ta film on the oxidation and the incorporation of [TaOH] was also studied. Angle-resolved X-ray photoelectron spectroscopy was used to study the composition of the surface oxide – specifically, the prevalence of Ta2O5 on the surface, with suboxides of Ta closer to the interface with metallic Ta, with thickness information obtained from transmission electron microscopy. It has been hypothesized [3] that TLS are not uniformly distributed throughout the oxide - our observations not only substantiate that hypothesis but indicate that hydroxyls are a possible molecular origin for such TLS. In a fashion analogous to studies of aluminum oxide [4], where the rotational freedom of the [OH] bond is suggested to be a source of the TLS, it is possible that [OH] plays a similar role in tantalum oxides as well. We also explore ways to modulate TaOH using nitridization on the Ta surface. Our findings provide ways to mitigate the effects of two-level systems in superconducting quantum devices.

[1] S. Papa Rao *et al.*, *Electrochem. Soc. Trans.* **85** (6), 151 (2018).

[2] N.P. de Leon *et al.*, *Science* **372**, eabb2823 (2021).

[3] K. D. Crowley *et al.*, *Phys. Rev. X* **13**, 4 (2023).

[4] L. Gordon *et al., Sci. Rep.* **4**, 7590 (2014).

9:30am **QS-TuM-7 Identifying and Mitigating Sources of Loss in Superconducting Qubits**, ***Akshay Murthy***, *M. Bal, F. Crisa, S. Zhu, D. Bafia, J. Lee, A. Romanenko, A. Grassellino,* Fermilab **INVITED**

Advances in our understanding of materials has played a crucial role driving recent increases in achievable coherence times and gate fidelities in superconducting transmon qubits. This includes identifying defects, impurities, interfaces, and surfaces present within the device geometry as well as implementing new strategies to mitigate the deleterious effects introduced by these disordered regions. As part of the Superconducting Quantum Materials and Systems (SQMS) center, we have deployed a wide variety of unique materials characterization techniques in tandem with microwave measurements to examine sources of loss in these devices. These include materials characterization techniques such as scanning/transmission electron microscopy, x-ray diffraction/reflectivity, scanning probe microscopy, secondary ion mass spectrometry, and atom probe tomography performed at both room temperature and cryogenic temperatures in addition to microwave loss measurements leveraging high quality factor superconducting radiofrequency (SRF) cavities. Through this effort, researchers have identified a wide variety of defective structures that serve as sources of two-level systems (TLS) or non-TLS dissipation as well as estimate their relative impacts to build a hierarchy of losses.

In this talk, I will discuss our results demonstrating that the surface oxide associated with superconducting niobium metal serves as a major source of microwave loss and that this loss scales with oxygen vacancies present in this oxide region. Based on this insight, we encapsulate the surface of niobium with various metal and dielectric layers that eliminate and prevent the formation of this lossy niobium surface oxide upon exposure to air and systematically achieve coherence times on the order of hundreds of microseconds. In order to continue to extend coherence times such that they reproducibly exceed beyond a millisecond, the loss hierarchy we have developed indicates that additional materials development to eliminate loss associated with the underlying substrate as well as the Josephson junction is needed. During the second half of my talk, I will discuss ongoing efforts in this area as well as the progression along our Quantum Technology roadmap that will move us from individual qubits to scalable, high coherence, multi-qubit platforms.

11:00am **QS-TuM-13 Dielectric Loss and Two-Level Systems in Superconducting Qubits*, Chen Wang*,** University of Massachusetts **INVITED**

Superconducting circuits are one of the leading technology platforms for the development of a practical quantum computer.In superconducting quantum circuits, qubits are typically constructed from Al/AlOx/Al Josephson tunnel junctions and patterned superconducting thin films such as Al, Nb, Ta on crystalline Si or sapphire substrate, and operated with external microwave pulses.Superconducting qubits enjoy advantages in their circuit design flexibilities, lithographic scalability, and operational clock speed, but must overcome decoherence and parameter variability and fluctuations from the solid-state environment.In particular, microwave noise from dielectric materials, including the Josephson junction, the bulk substrate, and various interfaces, have increasingly stood out as a limiting factor for both the lifetime and frequency stability of superconducting qubits.Such dielectric dissipation and fluctuation have been attributed to the omni-presence of a large number of discrete microscopic two-level systems (TLS) over an extremely broad frequency ranges (from kHz to GHz).Various improvements in qubit design and materials processing have led to substantial improvement of qubit coherence over the past decade through the mitigation of the TLS problem, but any atomistic understanding of these TLS in relevant materials remains elusive.In this talk, I will give a birds-eye view of the phenomenological studies of dielectric loss and two-level systems in superconducting circuits, and explain how the dream of building a quantum computer has been intertwined with so-far the most sensitive probe and the most demanding quest of traditional but pristine materials.

11:30am **QS-TuM-15 Measuring Loss Tangents of Substrates for Superconducting Qubits with Part per Billion Precision*, Daniel Bafia*,** *A. Murthy, A. Lunin, G. Nahal, A. Clairmont, M. Bal, A. Romanenko, A. Grassellino,* Fermi National Accelerator Laboratory

This talk will present a comparative study on the dielectric loss tangent of various substrates measured with an ultra-high quality factor niobium SRF cavity at the low electric fields and mK temperatures relevant for superconducting quantum computing architectures. We study the loss tangent evolution of c-plane sapphire post various treatments and correlate the resulting performance with materials analysis including time-of-flight secondary ion mass spectrometry and atomic force microscopy and report on key findings.

This material is based upon work supported by the U.S. Department of Energy, Office of Science, National Quantum Information Science Research Centers, Superconducting Quantum Materials and Systems Center (SQMS) under contract number DE-AC02-07CH11359.

11:45am **QS-TuM-16 Enhanced Qubit Frequency Targeting and Quantum Gate Fidelities in a 25-Qubit Superconducting Quantum Processor*, Amr Osman*,** *L. Chen, H. Li, A. Nylander, M. Rommel, S. Hill, E. Moschandreou, D. Shiri, M. Faucci Giannelli, A. Fadavi Roudsari, G. Tancredi, J. Bylander,* Chalmers University of Technology, Gothenburg, Sweden **INVITED**

Crosstalk poses a significant challenge to the scalability of superconducting quantum processors. This issue can be mitigated by implementing a careful frequency crowding scheme that ensures sufficient separation between neighboring quantum gate frequencies. Nevertheless, deviations in the fabrication process from the design parameters can undermine this scheme, leading to reduced qubit-gate fidelities. In this study, we designed and fabricated a 25-qubit quantum processor in a flip-chip geometry using a specially tailored frequency allocation scheme for parametric-gate architectures [1]. We present an extensive characterization of parameter targeting in this quantum processor, exploring the uncertainties introduced by the flip-chip bonding, and discussing the implications for crosstalk and quantum-gate fidelities.

[1] A. Osman, J. Fernandez-Pendas, C. Warren, S. Kosen, M. Scigliuzzo, A. Frisk Kockum, G. Tancredi, A. Fadavi Roudsari, and J. Bylander, "Mitigation of frequency collisions in superconducting quantum processors," Phys. Rev. Res. 5, 043001 (2023).

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