Monday Afternoon, January 20, 2025

PCSI
Room Keahou I - Session PCSI-MoA1
Superconducting Qubits
Moderator: Chunhui (Rita) Du, Georgia Institute of Technology

2:00pm **PCSI-MoA1-1 Novel Josephson Effects in Superconductor-Semiconductor Systems***, M. Gupta, G. Graziano, C. Riggert, L. Shani, G. Menning,* University of Minnesota, USA*; M. Pendharkar,* Stanford University*; C. Dempsey, J. Dong,* University of California at Santa Barbara*; P. Lueb, J. Jung,* Eindhoven University of Technology, The Netherlands*; R. Mélin,* Institut Néel, CNRS/UGA, Grenoble, France*; E. Bakkers,* Eindhoven University of Technology, The Netherlands*; C. Palmstrøm,* University of California at Santa Barbara*; **Vlad S. Pribiag**,* University of Minnesota, USA **INVITED**

Superconducting nanostructures underpin the development of many promising quantum computing approaches and alternatives to conventional classical computing. Most work to date has focused on all-metallic Josephson junctions. Recent developments in materials synthesis and nanofabrication have enabled devices that combine superconducting and semiconducting properties. These provide new opportunities for science and technology that rely on the interplay between superconductivity, quantum confinement, ballistic transport and spin-orbit coupling, or which leverage gate-tuning of superconducting couplings. In this talk, I will present results from a few transport studies based on semiconducting nanowires and quantum wells coupled with superconductors. The talk will focus primarily on nanostructures with more than two superconducting terminals [1-4], which can be used to implement superconducting diodes and non-linear intermodulation with full electrostatic control or to realize unusual correlations between Cooper pairs, and could also serve as a platform for topological Josephson matter [5].

[1] M. Gupta *et al.,* arXiv:2312.17703 (2023).

[2] M. Gupta *et al.*, Nature Communications **14**, 3078 (2023).

[3] G. Graziano, M. Gupta *et al.*, Nature Communications **13**, 5933 (2022).

[4] G. Graziano *et al.*, Phys. Rev. B **101**, 054510 (2020).

[5] R. Riwar *et al.*, Nature Communications **7**, 11167 (2016).

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2:40pm **PCSI-MoA1-9 UPGRADED: First-Principles Studies of Schottky Barriers and Tunneling Properties at Al(111)/Si(111) and CoSi2(111)/Si(111) Interfaces***, **Johannes Kevin Nangoi**, C. Palmstrøm, C. Van de Walle,* University of California, Santa Barbara

There has been recent interest in using Al(111)/Si(111) and $CoSi_2$(111)/Si(111) interfaces in novel merged-element transmons, which are proposed successors to the standard transmon qubits used in superconducting quantum computing. We present comprehensive first-principles studies of these interfaces, studying the relaxations of the atoms near the interface, calculating the formation energies and Schottky barrier heights, and providing estimates of the Josephson critical currents based on the Simmons/Tsu-Esaki tunneling model. We find that the formation energies and Schottky barrier heights are very similar for all Al(111)/Si(111) structures, yet vary significantly for the $CoSi_2$(111)/Si(111) structures. We attribute this to the more covalent character of bonding at $CoSi_2$/Si, which leads to configurations with distinct atomic and electronic structure. Our estimated Josephson critical currents, which govern the behavior of merged-element transmons, provide insight into the trends as a function of Schottky barrier height. We show that desirable qubit frequencies of 4–5 GHz can be obtained with a Si barrier thickness of 5–10 nm, and demonstrate that the critical current density as a function of Schottky barrier height can be modeled based on the tunneling probability for a rectangular barrier. We compare with experimental results where available, and discuss the implications of our results for actual devices.

3:00pm **PCSI-MoA1-13 Epitaxial Niobium Titanium Nitride Thin Films for Superconducting Quantum Circuits***, **Christopher Richardson**, A. Thomas,* Laboratory for Physical Sciences*; E. Supple, B. Gorman,* Colorado School of Mines

Engineered superconducting thin film heterostructures are needed to create future generations of high-fidelity superconducting qubits. Through a structure-first approach, Plasma Assisted Molecular Beam Epitaxy is used to grow a niobium titanium nitride alloy superconductor directly on c-plane sapphire with an abrupt metamorphic interface. The ternary thin film, $Nb_{0.85}Ti_{0.15}N$, has an engineered lattice constant that is designed and synthesized to match the in-plane atomic spacing of aluminum nitride. The best annealed films exhibit improved surface roughness to achieve a root-mean-square surface roughness less than 1 Å and improved superconducting critical temperature over 16 K. All films exhibit high quality factors at low powers, non-saturating superconducting microwave loss-behavior at high powers, and low kinetic inductance. These engineered superconducting thin films are ideal for the creation of an epitaxial Josephson junction and qubit devices that operate at higher temperatures.

In addition to exploring optimal growth parameters to produce thin ternary nitride superconductors, trilayers of NbTiN-AlN-NbTiN have been grown. Some of these samples have been measured using atomic probe tomography allowing crystallinity, homogeneity, and continuity of the AlN tunnel barrier to be quantitatively determined on the nanometer scale.[1]

[1] E. Supple, C. J. K. Richardson, & B. Gorman, J. Vac. Sci. Tech. A (2024).

3:05pm **PCSI-MoA1-14 Interface-Sensitive Microwave Loss in Tantalum Films Grown on C-Plane Sapphire for Quantum Information Applications***, **Anthony McFadden**, T. Larson, S. Gill, A. Dixit,* NIST-Boulder*; J. Oh, L. Zhou,* Ames Laboratory*; F. Lecocq, R. Simmonds,* NIST-Boulder

Tantalum (Ta) has garnered much attention in the field of superconducting quantum computing recently because of multiple published reports showing a performance enhancement of Ta devices when compared to aluminum or niobium (Nb). Fabrication of high-performance Ta devices is thought to rely on the formation of the α-phase (body centered cubic) structure which typically requires heating the substrate during growth, while β-phase (tetragonal) Ta usually dominates the composition of films deposited at room temperature. Formation of two distinct elemental phases contrasts with niobium (Nb), which typically only forms α-phase thin films.

We systematically vary the growth temperature of sputtered Nb and Ta thin films deposited on c-plane sapphire (Al_2O_3(001)) resulting in thin films of β-Ta, mixed phase β- /α-Ta and α-Ta and Nb. The structural properties of the resulting thin films are measured with reflection high energy electron diffraction (RHEED), X-ray diffraction (XRD), atomic force microscopy (AFM), and transmission electron microscopy (TEM). Established lithography and dry etching processes are used to fabricate Hall bars for DC transport measurements and superconducting coplanar-waveguide resonators for microwave characterization in a dilution refrigerator.

Our measurements show that the structural and DC electrical properties of both Nb and Ta films are mostly consistent with prior reports, however, it was found that the microwave performance of superconducting resonators made from epitaxial Ta(111) films grown directly on Al_2O_3(001) was markedly poor. Considering these findings, the Ta/Al_2O_3(001) interface was tested by inserting either a thin, epitaxial Nb interlayer or by amorphizing the sapphire surface before Ta growth using an *in-situ* Ar plasma. Both of these approaches were found to enhance the internal quality factor (Q_i) of the superconducting resonators by nearly two orders of magnitude. This suggests that the epitaxial Ta(111)/Al_2O_3(001) interface is a significant source of microwave loss, which may be mitigated by modifying the sapphire surface before growth. Possible origins of this loss and methods to characterize and mitigate it will also be discussed.

3:10pm **PCSI-MoA1-15 Cryogenically Grown a-Ta on Inas for 2DEG-Based Josephson Junctions***, **Teun van Schijndel**, J. Dong,* UC Santa Barbara*; Y. Gul,* University College London, UK*; D. Vera,* University of San Diego*; W. Yánez-Parreño, S. Chatterjee, C. Palmstrøm,* UC Santa Barbara

Josephson Junctions (JJs) are critical components in superconducting quantum circuits, including qubits, because of their nonlinear inductance [1]. Most commonly, JJ's in qubits consist of two aluminum superconductors separated by a thin aluminum oxide barrier. However, external control over the critical current and thus frequency of the qubit can only be achieved by applying magnetic flux through a superconducting quantum interference device. An alternative approach uses a semiconductor-superconductor heterostructure, allowing electric gate control of the JJ's critical current. In these systems, disorder, often introduced by superconductor/semiconductor interfacial reactions and during nanofabrication processes such as etching, can lead to heightened surface scattering [2], potentially leading to loss or decoherence.

Here, we are exploring the growth of Ta on InAs 2DEGs using a shadow mask technique in a low-temperature molecular beam epitaxy (MBE) system. This approach aims to eliminate nanofabrication-induced disorder near the junction. The 2DEGs are grown in an III-V MBE system, achieving mobilities exceeding 10^4 $cm^2/V{\cdot}s$. After growth, the InAs samples were capped with As. Before shadow mask deposition, the As cap was removed *in situ* by atomic hydrogen anneal. Reflective high energy electron diffraction (RHEED), scanning tunneling microscopy (STM), and X-ray photo spectroscopy (XPS) are used to investigate the semiconductor starting surface, the superconductor growth mode, and the extent of interfacial reactions. The Ta is grown at cryogenic temperatures (~7 K) to minimize interfacial reactions and to ensure the formation of the superconducting a-phase [3], allowing for the formation of highly transparent superconducting contacts. After optimization of the growth and resulting interface, JJ devices are fabricated using a shadow mask. Low-temperature electrical measurements (around 60 mK) are performed to determine the junction properties, including the critical current (Ic), the I_cR_n product, and the $I_{ex}R_n$ product. These values will allow us to evaluate the transparency of the superconducting contacts and determine if the junctions exhibit ballistic transport behavior. Comparisons will be made for Ta films grown at different substrate temperatures and we will report on correlations between interfacial reactions and Ta crystal structure with junction properties.

[1] P. Krantz, et al., Appl. Phys. Rev. 6, 021318 (2019)

[2] S. J. Pauka, et al., J. Appl. Phys. 128, 114301 (2020)

[3] T.A.J. van Schijndel, et al., arXiv preprint arXiv:2405.12417 (2024)

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3:15pm **PCSI-MoA1-16 Low Temperature Deposition of Superconducting Aluminum Films for Quantum Information Applications***, **Wilson J. Yánez-Parreño**, T. van Schijndel,* University of California at Santa Barbara*; A. McFadden, R. Simmonds,* NIST-Boulder*; C. Palmstrom,* University of California at Santa Barbara

Aluminum is one of the most widely adopted superconductors for quantum information applications [1, 2]. It has well understood superconducting properties and a self-limiting oxide that is an ideal barrier in Josephson junction devices [1]. This together with the ability to grow it in a clean manner on low dielectric loss substrates like sapphire and silicon makes it the material of choice to make quantum information devices like transmon qubits [2], Nevertheless, a big disadvantage of superconducting aluminum is its low critical field of around Hc=100 Oe and critical temperature of Tc=1.2K which makes it non ideal in quantum applications that require higher temperatures or an applied magnetic field.

We explore the growth of superconducting aluminum films on c-plane sapphire and silicon (111) at room temperature and cryogenic temperatures of < 20 K during deposition. The films are synthesized in state of the art low-temperature molecular beam epitaxy equipment with in-situ reflection high energy electron diffraction (RHEED) characterization and a base pressure of < 5E-11 mbar. We characterize the structure and crystallinity of the films, the substrate and the interface using x-ray diffraction, RHEED, atomic force microscopy and X-ray photoelectron spectroscopy. We measure electrical transport in these films under perpendicular magnetic fields and temperatures as low as 70 mK and correlate the superconducting properties of aluminum with its structure. We find that low temperature deposition increases the degree of structural disorder which enhances the critical temperature and critical field of aluminum to Tc=1.5K and Hc = 690 Oe. We then fabricate superconducting microwave resonators on these films and study the loss in aluminum grown at cryogenic temperatures.

[1] C. R. H. McRae, et al. Review of Scientific Instruments 91 (2020).

[2] Aute, F., et al. Nature 574, 505-510 (2019).

3:20pm **PCSI-MoA1-17 Strong Photon-Magnon Coupling Using a Lithographically Defined Organic Ferrimagnet***, Q. Xu, H. Cheung,* Cornell University*; D. Cormode,* The Ohio State University*; T. Puel,* University of Iowa*; S. Pal,* Cornell University*; H. Yusuf,* The Ohio State University*; M. Chilcote,* Cornell University*; M. Flatté,* University of Iowa*; **Ezekiel Johnston-Halperin**,* The Ohio State University*; G. Fuchs,* Cornell University

Hybrid quantum systems are attractive for emerging quantum technologies because they take advantage of the distinct properties of the constituent excitations. This is important because no single quantum system is ideal for every task, e.g., scalable quantum information processing, quantum sensing, long-lived quantum memory, and long-range quantum communication all have different requirements. In creating hybrid systems, it is advantageous to operate in the strong-coupling, low-loss regime, where the relaxation rates of the two distinct quantum systems are exceeded by the coupling rate between them. This allows the hybrid system to operate as a quantum interconnect, wherein quantum information can be passed from one excitation to another. Thus, a central challenge is to couple distinct quantum systems strongly, with all elements maintaining long coherence times. An equally critical challenge is to fabricate the hybrid quantum devices using scalable and integrable approaches so that their engineered properties can be used in applications.

Here we demonstrate a cavity-magnonic system composed of a superconducting microwave resonator coupled to a magnon mode hosted by the organic-based ferrimagnet vanadium tetracyanoethylene (V[TCNE]x) [1]. This work is motivated by the challenge of scalably integrating a low-damping magnetic system with planar superconducting circuits. V[TCNE]x has ultra-low intrinsic damping, can be grown at low processing temperatures on arbitrary substrates, and can be patterned via electron beam lithography. The devices operate in the strong coupling regime, with a cooperativity exceeding 1000 for coupling between the Kittel mode and the resonator mode at T≈0.4 K, suitable for scalable quantum circuit integration. This is critically enabling for integration and scaling, permitting future designs in which magnonic waveguides can be tailored as couplers or can mediate interactions between different quantum excitations in a planar superconducting circuit. Focusing on the 3.6 GHz device, we present a detailed microwave transmission spectrum that reveals not only the expected avoided level crossing of the resonator mode and the uniform magnon mode (the Kittel mode, or simply magnon mode unless otherwise stated) but also the resonator mode is hybridized with a discrete spectrum of higher-order magnon modes that show a much narrower linewidth than the uniform mode (Fig. 1). This work paves the way for future hybrid magnonic quantum systems by establishing an integrated and scalable platform enabling arbitrary design of the magnonic elements.

[1] Q. Xu, *et al. Advanced Science*, 2310032 (2024); DOI: 10.1002/advs.202310032

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